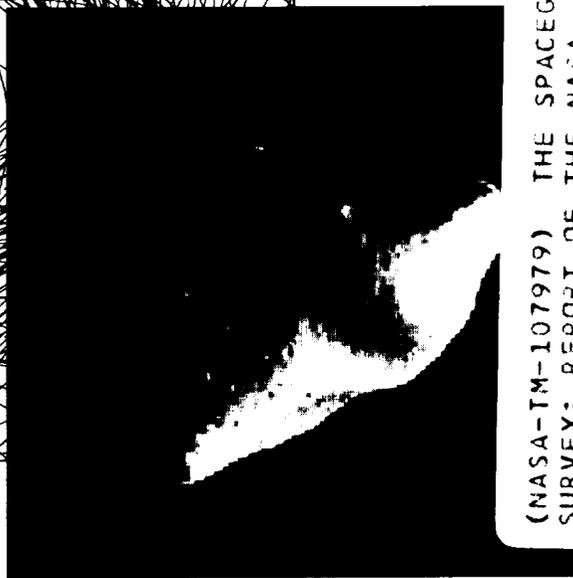
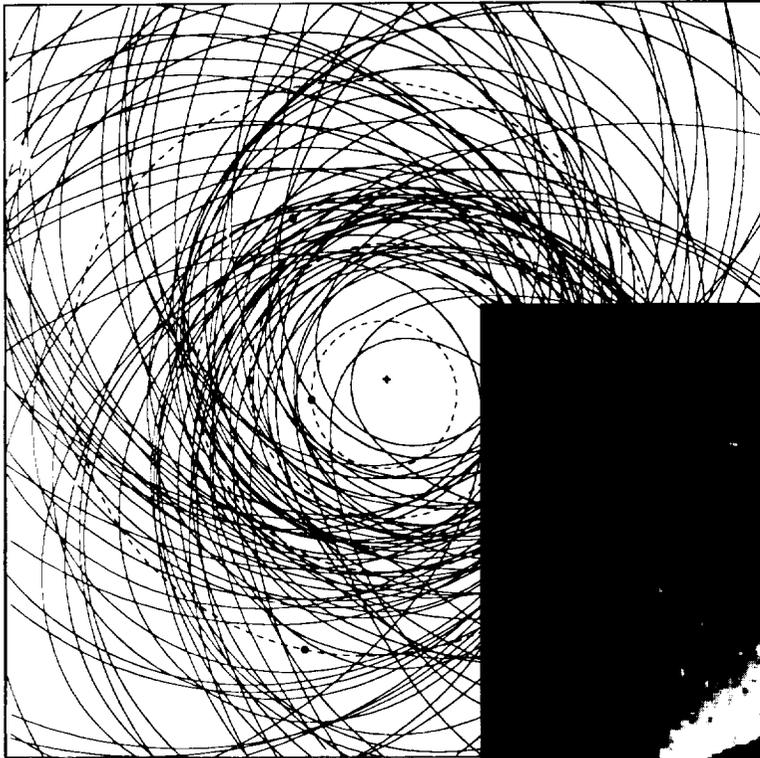


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(NASA-TM-107979) THE SPACEGUARD
SURVEY: REPORT OF THE NASA
INTERNATIONAL NEAR-EARTH-OBJECT
DETECTION WORKSHOP (NASA) 34 0

Report of the NASA International Near-Earth-Object Detection Workshop

David Morrison, Chair

January 25, 1992

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Cover: An image of 951 Gaspra, the only asteroid yet imaged by a spacecraft, overlays a diagram of the orbits of the inner planets and 100 of the largest known near-Earth asteroids.

January 25, 1992

The Spaceguard Survey:

Report of the

NASA International

Near-Earth-Object

Detection Workshop

edited by
David Morrison

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January 25, 1992

EXECUTIVE SUMMARY

Report of the NASA International Near-Earth Object Detection Workshop

Background. Impacts by Earth-approaching asteroids and comets pose a significant hazard to life and property. Although the annual probability of the Earth being struck by a large asteroid or comet is extremely small, the consequences of such a collision are so catastrophic that it is prudent to assess the nature of the threat and to prepare to deal with it. The first step in any program for the prevention or mitigation of impact catastrophes must involve a comprehensive search for Earth-crossing asteroids and comets and a detailed analysis of their orbits. At the request of the U.S. Congress, NASA has carried out a preliminary study to define a program for dramatically increasing the detection rate of Earth-crossing objects, as documented in this Workshop Report.

Impact Hazard. The greatest risk from cosmic impacts is associated with objects large enough to disturb the Earth's climate on a global scale by injecting large quantities of dust into the stratosphere. Such an event would depress temperatures around the globe, leading to massive loss of food crops and possible breakdown of society. Such global catastrophes are qualitatively different from other more common hazards that we face (excepting nuclear war), because of their potential effect on the entire planet and its population. The possibility of such a global catastrophe is beyond question, but determining the threshold impactor size to trigger such an event is more difficult. Various studies have suggested that the minimum mass impacting body to produce such global consequences is several tens of billions of tons, resulting in a groundburst explosion with energy approaching a million megatons of TNT. The corresponding threshold diameter for Earth-crossing asteroids or comets is between 1 and 2 km. Smaller objects (down to tens of meters diameter) can cause severe local damage but pose no global threat.

Search Strategy. Current technology permits us to discover and track nearly all asteroids or short-period comets larger than 1 km diameter that are potential Earth-impactors. These objects are readily detected with moderate-size ground-based telescopes. Most of what we now know about the population of Earth-crossing asteroids (ECAs) has been derived over the past two decades from studies carried out by a few dedicated observing teams using small ground-based telescopes. Currently, several new ECAs are discovered each month. At this rate, however, it will require several centuries to approach a complete survey, even for the larger objects. What is required to assess the population of ECAs and identify any large objects that could impact the Earth is a systematic survey that effectively monitors a large volume of space around our planet and detects these objects as their orbits repeatedly carry them through this volume of space. In addition, the survey should deal with the long-period comets, which are thought to constitute about 5 to 10 percent of the flux of Earth impactors. Long-period comets do not regularly enter near-Earth space; however, most Earth-impacting long-period comets could be detected with advance warning several months before impact, using the same telescopes used for the ECA survey. Finally, it is desirable to discover as many of the smaller potential impactors as possible.

Lead Time. No object now known has an orbit that will lead to a collision with our planet during the next few centuries, and the vast majority of the newly discovered asteroids and comets will also be found to pose no near-term danger. Even if an ECA has an orbit that might lead to an impact, it will typically make hundreds of moderately near passes before there is any danger, providing ample time for response. However, the lead time will be much less for a comet approaching the Earth on a long-period orbit.

Spaceguard Survey Network. The survey outlined in this report involves a coordinated international network of specialized ground-based telescopes for discovery, confirmation, and follow-up observations. Observations are required from both the northern and southern hemispheres, monitoring about 6,000 square degrees of sky per month. In order to provide reliable detection of objects as small as 1 km diameter within a suitably large volume of space,

the telescopes should reach astronomical magnitude 22. The telescopes that are suitable to this survey have apertures of 2 to 3 meters, moderately wide fields of view (2 to 3 degrees), focal-plane arrays of large-format charge-coupled device (CCD) detectors, and automated signal processing and detection systems that recognize the asteroids and comets from their motion against the background of stars. The technology for such automated survey telescopes has been developed and demonstrated by the 0.9-m Spacewatch telescope of the University of Arizona. For purposes of this study, we focus on a Spaceguard Survey network of six 2.5-m aperture, f/2 prime focus reflecting telescopes, each with four 2048x2048 CCD chips in the focal plane.

Follow-up and Coordination. *In addition to the discovery and verification of new Earth-approaching asteroids and comets, the Spaceguard Survey program will require follow-up observations to refine orbits, determine the sizes of newly discovered objects, and establish the physical properties of the asteroid and comet population. Observations with large planetary radars are an especially effective tool for the rapid determination of accurate orbits. Radar data will be required to ascertain whether potentially hazardous objects will miss the Earth or, if this is not the case, to determine the exact time and location of the impact. Desirable for this program would be increased access to currently operational planetary radars in California and Puerto Rico, and provision of a suitable southern-hemisphere radar in the future. Although one or more dedicated follow-up telescopes would greatly improve our ability to study faint and distant asteroids and comets, we anticipate that much of the optical follow-up work can be accomplished with the survey telescopes themselves if they are suitably instrumented. The survey program also requires rapid international electronic communications and a central organization for coordination of observing programs and maintenance of a database of discovered objects and their orbits.*

Expected Survey Results. *Numerical modeling of the operation of the Spaceguard Survey network indicates that about 500 ECAs will be discovered per month. Over a period of 25 years we will identify more than 90 percent of potentially threatening ECAs larger than 1 km in diameter; a dark-sky survey will detect most incoming comets several months before they approach the Earth. At the same time, tens of thousands of smaller asteroids (down to a few meters in diameter) will also be discovered, although the completeness of the survey declines markedly for objects smaller than about 500 m. The advantage of this survey approach is that it achieves the greatest level of completeness for the largest and most dangerous objects; however, if continued for a long period of time, it will provide the foundation for assessing the risk posed by smaller impacts as well. Continued monitoring of the sky will also be needed to provide an alert for potentially hazardous long-period comets.*

Cost of the Spaceguard Survey. *The survey can begin with current programs in the United States and other countries, which are providing an initial characterization of the ECA population and can serve as a testbed for the technologies proposed for the new and larger survey telescopes. A modest injection of new funds into current programs could also increase current discovery rates by a factor of two or more, as well as provide training for personnel that will be needed to operate the new survey network. For the new telescopes, we assume the use of modern technology that has, over the past decade, substantially reduced the construction costs of telescopes of this aperture. The initial cost to build six 2.5-m telescopes and to establish a center for program coordination is estimated to be about \$50M (FY93 dollars), with additional operating expenses for the network of about \$10M per year. If construction were begun in FY93, the survey could be in operation by about 1997.*

Conclusions. *The international survey program described in this report can be thought of as a modest investment to provide insurance for our planet against the ultimate catastrophe. The probability of a major impact during the next century is very small, but the consequences of such an impact, especially if the object is larger than about 1 km diameter, are sufficiently terrible to warrant serious consideration. The Spaceguard Survey is an essential step toward a program of risk reduction that can reduce the risk of an unforeseen cosmic impact by more than 75 percent over the next 25 years.*

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The Earth resides in a swarm of asteroids and comets that can, and do, impact its surface (Figs. 1-1 and 1-2). The solar system contains a long-lived population of asteroids and comets, some fraction of which are perturbed into orbits that cross the orbits of the Earth and other planets. Spacecraft exploration of the terrestrial planets and the satellites of the outer planets has revealed crater-scarred surfaces that testify to a continuing rain of impacting projectiles. Additional evidence concerning cosmic projectiles in near-Earth space has accumulated since the discovery of the first recognized Earth-crossing asteroid nearly sixty years ago, and improvements in telescopic search techniques have resulted in the discovery of dozens of near-Earth asteroids and short-period comets each year. The role of impacts in affecting the Earth's geological history, its ecosphere, and the evolution of life itself has become a major topic of current interdisciplinary interest.

Significant attention by the scientific community to the hazard began in 1980 when Luis Alvarez and others proposed that such an impact, and the resulting global pall of dust, resulted in mass extinctions of lifeforms on Earth, ending the age of the dinosaurs (Alvarez and others, 1980). Additional papers and discussion in the scientific literature followed, and widespread public interest was aroused. In 1981, NASA organized a workshop, "Collision of Asteroids and Comets with the Earth: Physical and Human Consequences" at Snowmass, Colorado (July 13-16, 1981). A summary of the principal conclusions of the workshop report appeared in the book *Cosmic Catastrophes* (Chapman and Morrison, 1989a) and in a

presentation by Chapman and Morrison (1989b) at an American Geophysical Union Natural Hazards Symposium. In response to the close passage of asteroid 1989 FC, the American Institute of Aeronautics and Astronautics (AIAA, 1990) recommended studies to increase the detection rate of near-Earth asteroids, and how to prevent such objects striking the Earth. The AIAA brought these recommendations to the attention of the House Committee on Science, Space and Technology, leading to the Congressional mandate for this workshop included in the NASA 1990 Authorization Bill. In parallel with these political developments, a small group of dedicated observers significantly increased the discovery rate of near-Earth asteroids and comets, and several of these discoveries were highlighted in the international press. Other recent activity has included the 1991 International Conference on Near-Earth Asteroids (San Juan Capistrano, California, June 30 - July 3), a meeting on the "Asteroid Hazard" held in St. Petersburg, Russia (October 9-10, 1991), and a resolution endorsing international searches for NEOs adopted by the International Astronomical Union (August 1991).

Despite a widespread perception that asteroid impact is a newly recognized hazard, the basic nature of the hazard was roughly understood half a century ago. In 1941, Fletcher Watson published an estimate of the rate of impacts on the Earth, based on the discovery of the first three Earth-approaching asteroids (Apollo, Adonis, and Hermes). A few years later, Ralph Baldwin, in his seminal book *The Face of the Moon* (1949), wrote

...since the Moon has always been the companion of the Earth, the history of the former is only a para-

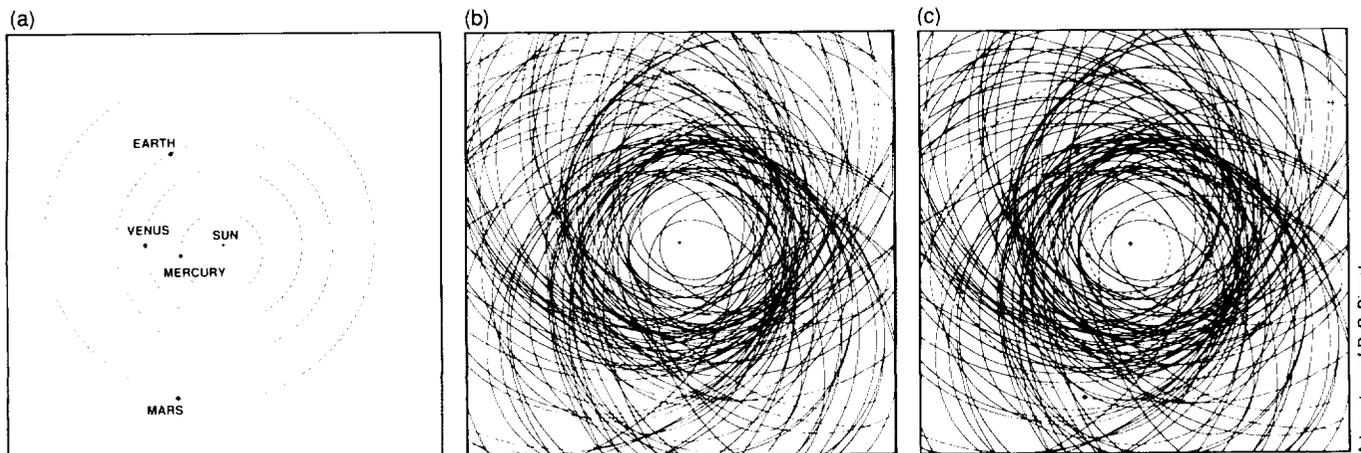


Figure 1-1. Earth resides in a swarm of comets and asteroids, as this series of plots graphically shows: (a) the locations of the inner planets on January 1, 1992, (b) the orbits of the 100 largest known near-Earth asteroids, and (c) composite of (a) and (b).

Art courtesy of R. P. Binzel



Photograph courtesy of R. J. Roddy and K. A. Zeller, U.S. Geological Survey

Figure 1-2. An aerial view of Meteor Crater, Arizona, one of the Earth's youngest impact craters. Field studies indicate that the crater was formed some 50,000 years ago by an iron mass(es) traveling in excess of 11 km/s and releasing 10 to 20 megatons of energy. The result was the formation of a bowl-shaped crater approximately 1 km across and over 200 m deep, surrounded by an extensive ejecta blanket.

phrase of the history of the latter... [Its mirror on Earth] contains a disturbing factor. There is no assurance that these meteoritic impacts have all been restricted to the past. Indeed we have positive evidence that [sizeable] meteorites and asteroids still abound in space and occasionally come close to the Earth. The explosion that formed the [lunar] crater Tycho... would, anywhere on Earth, be a horrifying thing, almost inconceivable in its monstrosity.

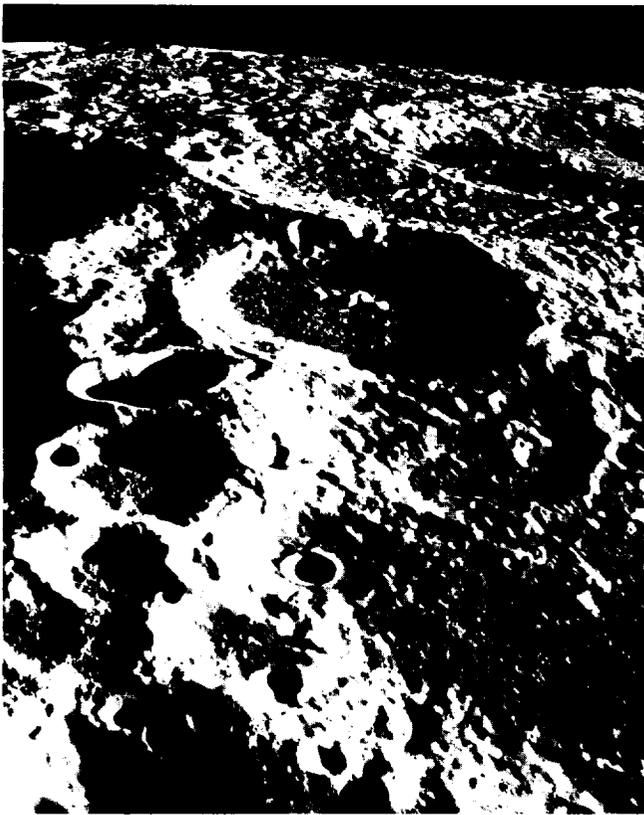
Watson and Baldwin (both of whom are still alive) were prescient, but in their time few other scientists gave much thought to impacts on the Earth. Recently, however, there has been a gestalt shift that recognizes extraterrestrial impact as a major geological process and, probably, an important influence on the evolution of life on our planet (Figs. 1-3 and 1-4). Also new is our capability to detect such objects and to develop a space technology that could deflect a potential projectile before it struck the Earth.

1.2 THE INTERNATIONAL NEO DETECTION WORKSHOP

The United States House of Representatives, in its NASA Multiyear Authorization Act of 1990 (26 September 1990), included the following language:

"The Committee believes that it is imperative that the detection rate of Earth-orbit-crossing asteroids must be increased substantially, and that the means to destroy or alter the orbits of asteroids when they threaten collision should be defined and agreed upon internationally.

"The chances of the Earth being struck by a large asteroid are extremely small, but since the consequences of such a collision are extremely large, the Committee believes it is only prudent to assess the nature of the threat and prepare to deal with it. We have the technology to detect such asteroids and to prevent their collision with the Earth.



Photograph courtesy of NASA/Johnson Space Center

Figure 1-3. The heavily cratered highlands of the Moon record the period of heavy bombardment that marked the first 500 million years of lunar history.

“The Committee therefore directs that NASA undertake two workshop studies. The first would define a program for dramatically increasing the detection rate of Earth-orbit-crossing asteroids; this study would address the costs, schedule, technology, and equipment required for precise definition of the orbits of such bodies. The second study would define systems and technologies to alter the orbits of such asteroids or to destroy them if they should pose a danger to life on Earth. The Committee recommends international participation in these studies and suggests that they be conducted within a year of the passage of this legislation.”

The present report of the NASA International Near-Earth-Object Detection Workshop is the direct result of this Congressional request to NASA. A second NASA workshop on the question of altering asteroid orbits is scheduled for January 1992.

The NASA International Near-Earth-Object Detection Workshop was organized in the spring of 1991 and held three formal meetings: on June 30 - July 3 at the San Juan Capistrano Research Institute, on September 24-25 at the NASA Ames Research Center, and on November 5 in Palo Alto, California. The group has the following membership of 24 individuals from four continents:

- Richard Binzel (Massachusetts Institute of Technology, USA)
- Edward Bowell (Lowell Observatory, USA)
- Clark Chapman (Planetary Science Institute, USA)
- Louis Friedman (The Planetary Society, USA)
- Tom Gehrels (University of Arizona, USA)
- Eleanor Helin (Caltech/NASA Jet Propulsion Laboratory, USA)
- Brian Marsden (Harvard-Smithsonian Center for Astrophysics, USA)
- Alain Maury (Observatoire de la Côte d’Azur, France)
- Thomas Morgan (NASA Headquarters, USA)
- David Morrison (NASA Ames Research Center, USA)
- Karri Muinonen (University of Helsinki, Finland)
- Steven Ostro (Caltech/NASA Jet Propulsion Laboratory, USA)
- John Pike (Federation of American Scientists, USA)
- Jurgen Rahe (NASA Headquarters, USA)
- R. Rajamohan (Indian Institute of Astrophysics, India)
- John Rather (NASA Headquarters, USA)
- Kenneth Russell (Anglo-Australian Observatory, Australia)
- Eugene Shoemaker (U.S. Geological Survey, USA)
- Andrej Sokolsky (Institute for Theoretical Astronomy, Russia)
- Duncan Steel (Anglo-Australian Observatory, Australia)
- David Tholen (University of Hawaii, USA)
- Joseph Veverka (Cornell University, USA)
- Faith Vilas (NASA Johnson Space Center, USA)
- Donald Yeomans (Caltech/NASA Jet Propulsion Laboratory, USA)

1.3 APPROACH TO THE PROBLEM

As described in the following chapters of this report, the workshop group has analyzed the nature of the hazard and devised an example of a practical program for the detection of potentially catastrophic cosmic impacts. The greatest risk is from the impact of the largest near-Earth Objects (NEOs) — those

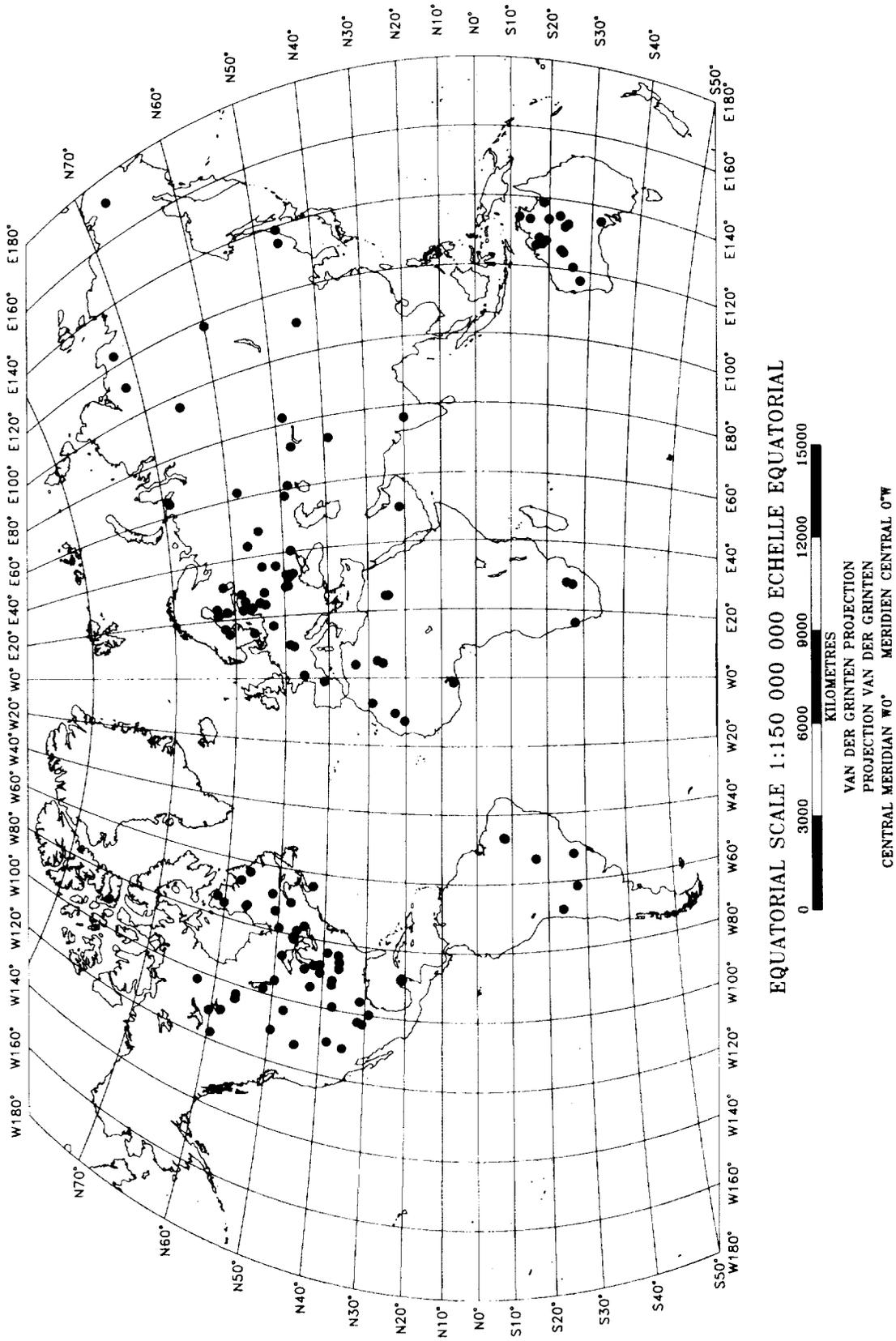


Figure 1-4. Approximately 130 terrestrial impact craters have been identified. They range up to 140 to 200 km in diameter and from recent to about two billion years in age. More craters have been identified in Australia, North America, and eastern Europe partly because these areas have been relatively stable for considerable geologic periods, thus preserving the early geologic record, and because active search programs have been conducted in these areas.

Art courtesy of R. A. F. Grieve, Geological Survey of Canada

with diameters greater than 1 km. Such impacts, which occur on average from once to several times per million years, are qualitatively as well as quantitatively different from any other natural disasters in that their consequences are global, affecting the entire planet. How, then, should we approach the problem of discovering and tracking these objects?

About 90 percent of the potential Earth-impacting projectiles are near-Earth asteroids or short-period comets; the other 10 percent are intermediate- or long-period comets having orbital periods longer than 20 years. Collectively, these bodies are called NEOs (near-Earth objects). Most NEOs have orbits that closely approach or at some time intersect Earth's orbit, although the intermediate- and long-period comets spend very little time in near-Earth space. Their normal orbital motion brings most near-Earth asteroids relatively near the Earth every few years, and it is during such approaches that they have hitherto been discovered. The objective of the extensive NEO survey described here is to find most of the larger and potentially hazardous NEOs (not necessarily when they are near the Earth), to calculate their long-term orbital trajectories, and to identify any that may impact the Earth over the next several centuries. If any appear to be on Earth-impact trajectories, there will generally be a period of at least several decades during which to take corrective action. It should be emphasized that we are not discussing either a short-range search or a quick-response defense system. The chance that a near-Earth asteroid will be discovered less than a few years before impact is vanishingly small. The nature of the NEO orbits allows us to carry out a deliberate, comprehensive survey with ample time to react if any threatening NEO is found. In contrast, however, the warning time for impact from a long-period comet might be as short as a few months, requiring a different class of response.

In order to carry out a deliberate and comprehensive search, we must detect, over a period of a decade or more, the NEOs larger than our 1-km size threshold that pass near the Earth. This requires that we monitor a region of space extending outward from the orbit of the Earth approximately as far as the inner

edge of the main asteroid belt, at a distance of 200 million kilometers. The easiest way to detect these NEOs is by observing their reflected sunlight, although they can also be seen in the infrared using their emitted thermal radiation. More exotic technologies are not appropriate; radar, in particular, is limited to targets relatively close to the Earth, and is not suited to wide-field sky searches. In principle, the survey could be carried out either from the ground or from orbit. The brightness of a 1-km NEO at 200 million kilometers, assuming a reflectivity of 3 percent or more, corresponds to stellar magnitude 22. Although they are quite faint, such objects are readily detectable with conventional ground-based telescopes and can be distinguished from background stars by their characteristic motion. Thus there is no requirement for a more expensive space-based system. This brightness limit also determines the minimum telescope aperture of about 2 m that is required for a complete survey. Thus we have it within our current capability to construct a network of survey telescopes at relatively modest cost that can discover and track essentially all of the NEOs greater than 1 km in diameter. In addition, this same network of optical survey telescopes will be capable of detecting most incoming intermediate- or long-period comets and determining if any of them has the potential to strike the Earth. However, the time between detection and possible impact will be much shorter for the long-period comets, as already noted.

The survey program described in this report has the potential to alter fundamentally the way we view the threat of cosmic impacts. To date we have talked about a relatively undefined threat, to be discussed in terms of probabilities or statistical risks. While we know that such impacts must take place from time to time, we do not know if there are any specific bodies in space that might impact the Earth over the next few centuries. If this search program is carried out, however, we can answer this question to about the 75 percent confidence level. If such an object is found, then we can turn our attention to dealing with the threat it poses. In other words, we have the capability for a 75 percent reduction in the hazard posed by cosmic impacts.

CHAPTER 2

HAZARD OF COSMIC IMPACTS

2.1 INTRODUCTION

Throughout its history, the Earth has been impacted by countless asteroids and comets. Smaller debris continually strike Earth's upper atmosphere where they burn due to friction with the air (Fig. 2-1); meteors (which are typically no larger than a pea and have masses of about a gram) can be seen every night from a dark location if the sky is clear. Thousands of meteorites (typically a few kilograms in mass) penetrate the atmosphere and fall harmlessly to the ground each year. On rare occasions, a meteorite penetrates the roof of a building, sometimes injuring the occupants, although to date there are no fully documented human fatalities. A much larger event, however, occurred in 1908 when a cosmic fragment disintegrated in the atmosphere over Tunguska, Siberia, with an explosive energy of more than 10 megatons TNT. But even the Tunguska impactor was merely one of the smallest of Earth's neighbors in space. Of primary concern are the larger objects, at least one kilometer in diameter. Although very rare, the impacts of these larger objects are capable of severely damaging the Earth's ecosystem with a resultant massive loss of life.

In the following discussion, we examine the risks posed by impacting objects of various sizes. These projectiles could be either cometary or asteroidal. In terms of the damage they do, it matters little whether they would be called comets or asteroids by astronomical observers. We term these objects collectively NEOs (near-Earth objects).

Every few centuries, the Earth is struck by an NEO large enough to cause thousands of deaths, or hundreds of thousands of deaths if it were to strike in an urban area. On time scales of millennia, impacts large enough to cause damage comparable to the greatest known natural disasters may be expected to occur (Pike, 1991). Indeed, during our lifetime, there is a small but non-zero chance (very roughly 1 in 10,000) that the Earth will be struck by an object large enough to destroy food crops on a global scale and possibly end civilization as we know it (Shoemaker and others, 1990).

As described in Chapter 3, estimates of the population of NEOs large enough to pose a global hazard are reliable to within a factor of about two, although estimates of the numbers of smaller objects are more uncertain. Particularly uncertain is the significance of hard-to-detect long-period comets, which would generally strike at higher velocities than other NEOs (Olsson-Steel, 1987; Weissman, 1990), although as-

teroids (including dead comets) are believed to dominate the flux. However, the resulting environmental consequences of the impacts of these objects are much less well understood. The greatest uncertainty in comparing the impact hazard with other natural hazards relates to the economic and social consequences of impact-caused damage to the ecosphere. Little work has been done on this problem, but we summarize the consequences — to the degree they are understood — in this chapter.

2.2 THE RELATIONSHIP OF RISK TO SIZE OF IMPACTOR

Small impacting objects that produce ordinary meteors or fireballs dissipate their energy high in the upper atmosphere and have no direct effect on the ground below. Only when the incoming projectile is larger than about 10 m diameter does it begin to pose some hazard to humans. The hazard can be conveniently divided into three broad categories that depend on the size or kinetic energy of the impactor:

- (1) Impacting body generally is disrupted before it reaches the surface; most of its kinetic energy is dissipated in the atmosphere, resulting chiefly in local effects.



Photograph by James M. Baker, courtesy of Dennis Milton.

Figure 2-1. On August 10, 1972, an alert photographer in Grand Teton National Park recorded the passage of an object estimated at 10 m diameter and weighing several thousand tons. The object narrowly missed colliding with Earth's surface, although it burned in our atmosphere for 101 seconds as it travelled over 1,475 km at about 15 km/s.

- (2) Impacting body reaches ground sufficiently intact to make a crater; effects are still chiefly local, although nitric oxide and dust can be carried large distances, and there may be a tsunami if the impact is in the ocean.
- (3) Large crater-forming impact generates sufficient globally dispersed dust to produce a significant, short-term change in climate worldwide, in addition to devastating blast effects in the region of impact.

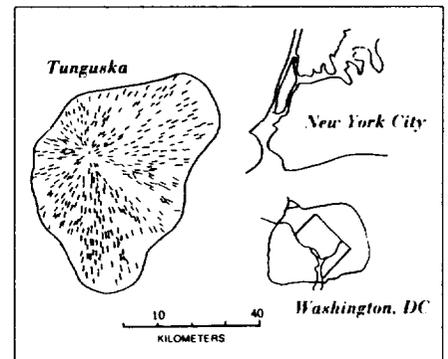
The threshold size of an impacting body for each category depends on its density, strength, and velocity. The threshold for global effects, in particular, is not well determined.

Category 1: 10 m to 100 m diameter impactors

Bodies near the small end of this size range intercept Earth every decade. Bodies about 100 m diameter and larger strike, on average, several times per millennium. The kinetic energy of a 10-m projectile traveling at a typical atmospheric entry velocity of 20 km/s is about 50 to 100 kilotons TNT equivalent, equal to several Hiroshima-size bombs. The kinetic energy of a 100-m diameter body is equivalent to the explosive energy of about 100 megatons, comparable to the yield of the very largest thermonuclear devices.

For the 10-m projectiles, only rare iron or stony-iron projectiles reach the ground with a sufficient fraction of their entry velocity to produce craters, as happened in the Sikhote-Alin region of Siberia in 1947. Stony bodies are crushed and fragmented during atmospheric deceleration, and the resulting fragments are quickly slowed to free-fall velocity, while the kinetic energy is transferred to an atmospheric shock wave. Part of the shock wave energy is released in a burst of light and heat (called a meteoric fireball) and part is transported in a mechanical wave. Generally, these 100-kiloton disruptions occur high enough in the atmosphere so that no damage occurs on the ground, although the fireball can attract attention from distances of 600 km or more and the shock wave can be heard and even felt on the ground.

With increasing size, asteroidal projectiles reach progressively lower levels in the atmosphere before disruption, and the energy transferred to the shock wave is correspondingly greater. There is a threshold where both the radiated energy from the shock and the pressure in the shock wave can produce damage. An historical example is the Tunguska event of 1908 (Fig. 2-2), when a body perhaps 60 m in diameter was disrupted in the atmosphere at an altitude of about 8 km. The energy released was about 12 megatons, as estimated from airwaves recorded on meteorological



Tunguska in perspective

Figure 2-2. On June 30, 1908, at 7:40 AM, a cosmic projectile exploded in the sky over Siberia. It flattened 2,000 square kilometers of forest in the Tunguska region. If a similar event were to occur over an urban area today, hundreds of thousands of people would be killed, and damage would be measured in hundreds of billions of dollars.

barographs in England, or perhaps 20 megatons as estimated from the radius of destruction. Siberian forest trees were mostly knocked to the ground out to distances of about 20 km from the endpoint of the fireball trajectory, and some were snapped off or knocked over at distances as great as 40 km. Circumstantial evidence suggests that fires were ignited up to 15 km from the endpoint by the intense burst of radiant energy. The combined effects were similar to those expected from a nuclear detonation at a similar altitude, except, of course, that there were no accompanying bursts of neutrons or gamma rays nor any lingering radioactivity. Should a Tunguska-like event happen over a densely populated area today, the resulting airburst would be like that of a 10- to 20-megaton bomb: buildings would be flattened over an area 20 km in radius, and exposed flammable materials would be ignited near the center of the devastated region.

An associated hazard from such a Tunguska-like phenomenon is the possibility that it might be misinterpreted as the explosion of an actual nuclear weapon, particularly if it were to occur in a region of the world where tensions were already high. Although it is expected that sophisticated nuclear powers would not respond automatically to such an event, the possible misinterpretation of such a natural event dramatizes the need for heightening public consciousness around the world about the nature of unusually bright fireballs.

Category 2: 100 m to 1 km diameter impactors

Incoming asteroids of stony or metallic composition that are larger than 100 m in diameter may reach the ground intact and produce a crater. The threshold size depends on the density of the impactor and its speed and angle of entry into the atmosphere. Evidence from the geologic record of impact craters, as well as theory, suggests that in the average case, stony objects greater than 150 m in diameter form craters. They strike the Earth about once per 5,000 years and — if impacting on land — produce craters about 2 km in diameter. A continuous blanket of material ejected from such craters covers an area about 10 km in diameter. The zone of destruction extends well beyond this area, where buildings would be damaged or flattened by the atmospheric shock, and along particular directions (rays) by flying debris. The total area of destruction is not, however, necessarily greater than in the case of atmospheric disruption of somewhat smaller objects, because much of the energy of the impactor is absorbed by the ground during crater formation. Thus the effects of small crater-forming events are still chiefly local.

Toward the upper end of this size range, the energy would so vastly exceed what has been studied

in nuclear war scenarios that it is difficult to be certain of the effects. Extrapolation from smaller yields suggests that the “local” zones of damage from the impact of a 1-km object could envelop whole states or countries, with fatalities of tens of millions in a densely populated region.

Comets are composed in large part of water ice and other volatiles and therefore are more easily fragmented than rocky or metallic asteroids. In the size range from 100 m to approaching 1 km, a comet probably cannot survive passage through the atmosphere, although it may generate atmospheric bursts sufficient to produce local destruction. This subject needs additional study, requiring a better knowledge of the physical nature of comets.

Category 3: 1 km to 5 km diameter impactors

At these larger sizes, a threshold is finally reached at which the impact has catastrophic global consequences, although much work remains to be done fully to understand the physical and chemical effects of material injected into the atmosphere. In general, the crater produced by these impacts has 10 to 15 times the diameter of the projectile; i.e., 10 to 15 km diameter crater for a 1-km asteroid. Such craters are formed on the continents about once per 300,000 years. At impactor sizes greater than 1 km, the greatest hazard derives from the global veil of dust injected into the stratosphere. The severity of the global effects of large impacts increases with the size of the impactor and the resulting quantity of injected dust. At some size, an impact would lead to massive world-wide crop failures and consequent mass mortality, and would threaten the survival of civilization. At still larger sizes, even the survival of the human species would be put at risk.

What happens when an object several kilometers in diameter strikes the Earth at a speed of tens of kilometers per second? Primarily there is a massive explosion, sufficient to fragment and partially vaporize both the projectile and the target. Meteoric phenomena associated with high-speed ejecta could subject plants and animals to scorching heat for about half an hour, and a continent-wide firestorm might then ensue. Dust thrown up from a very large crater would lead to daytime darkness over the whole Earth, which might persist for several months. Temperatures could drop as much as tens of degrees Celsius. Nitric acid, produced from the burning of atmospheric nitrogen in the impact fireball, would acidify lakes, soils, streams, and perhaps the surface layer of the oceans. Months later, after the atmosphere had cleared, water vapor and carbon dioxide released to the stratosphere would produce an enhanced greenhouse effect, possibly raising global temperatures by as much as 10°C above the pre-existing ambient

temperatures. This global warming might last for decades, as there are several positive feedbacks: warming of the surface increases the humidity of the troposphere, thereby increasing the greenhouse effect, and warming of the ocean surface releases carbon dioxide which also increases the greenhouse effect. Both the initial months of darkness and cold, and then the following years of enhanced temperatures, would severely stress the environment and would lead to drastic population reductions of both terrestrial and marine life.

2.3 THRESHOLD SIZE FOR GLOBAL CATASTROPHE

The threshold size of impactor that would produce one or all of the effects discussed above is not accurately known. The geochemical and paleontological record has demonstrated that one impact (or perhaps several closely spaced impacts) 65 million years ago of a 10- to 15-km NEO resulted in total extinction of about half the living species of animals and plants (Fig. 2-3) (Sharpton and Ward, 1990). This so-called K-T impact may have exceeded 100 million megatons in explosive energy. Such mass extinctions of species have recurred several times in the past few hundred million years; it has been suggested, although not yet proven, that impacts are responsible for most such extinction events. We know from astronomical and geological evidence that impacts of objects with diameters of 5 km or greater occur about once every 10 to 30 million years.

Death by starvation of much of the world's population could result from a global catastrophe far less horrendous than those cataclysmic impacts that would suddenly render a significant fraction of species actually extinct, but we know only very poorly what size impact would cause such mass mortality. In addition to all of the known variables (site of impact, time of year) and the uncertainties in physical and ecological consequences, there is the question of how resilient our agriculture, commerce, economy, and societal organization might prove to be in the face of such an unprecedented catastrophe.

These uncertainties could be expressed either as a wide range of possible consequences for a particular size (or energy) of impactor or as a range of impactor sizes that might produce a certain scale of global catastrophe. We take the second approach and express the uncertainty as a range of threshold impactor sizes that would yield a global catastrophe of the following proportions:

- It would destroy most of the world's food crops for a year, and /or



Photograph by Alan Hildebrand

Figure 2-3. A thin, bright layer of clay less than an inch wide (toward the end of the rock-hammer handle, separated from the thick bright sandstone by a narrow seam of coal) marks debris from the catastrophic event that ended the Cretaceous era 65 million years ago. Here the boundary is shown in an outcrop near Madrid, Colorado.

- It would result in the deaths of more than a quarter of the world's population, and/or
- It would have effects on the global climate similar to those calculated for "nuclear winter," and/or
- It would threaten the stability and future of modern civilization.

A catastrophe having one, or all, of these traits would be a horrifying thing, unprecedented in history, with potential implications for generations to come.

To appreciate the scale of global catastrophe that we have defined, it is important to be clear what it is not. We are talking about a catastrophe far larger than the effects of the great World Wars; it would result from an impact explosion certainly larger than if 100 of the very biggest hydrogen bombs ever tested were detonated at once. On the other hand, we are talking about an explosion far smaller (less than 1 percent of the energy) than the K-T impact 65 million years ago. We mean a catastrophe that would threaten modern civilization, not an apocalypse that would threaten the survival of the human species.

What is the range of impactor sizes that might lead to this magnitude of global catastrophe? At the July 1991 Near-Earth Asteroid Conference in San Juan Capistrano, California, the most frequently discussed estimate of the threshold impactor diameter for globally catastrophic effects was about 2 km. An estimate of the threshold size was derived for this Workshop in September 1991 by Brian Toon, of NASA/Ames Research Center. Of the various environmental effects of a large impact, Toon believes that the greatest harm would be done by the sub-micrometer dust launched into the stratosphere. This very fine dust

has a long residence time, and global climate modeling studies by Covey and others (1990) imply significant drops in global temperature that would threaten agriculture worldwide. The quantity of sub-micrometer dust required for climate effects equivalent to those calculated for nuclear winter is estimated at about 10,000 Teragrams (Tg) ($1 \text{ Tg} = 10^{12} \text{ g}$). For a 30 km/s impact, this translates to a threshold impacting body diameter of between 1 and 1.5 km diameter.

The threshold for an impact that causes widespread global mortality and threatens civilization almost certainly lies between about 0.5 and 5 km diameter, perhaps near 2 km. Impacts of objects this large occur from one to several times per million years.

2.4 RISK ANALYSIS

If this estimate of the frequency of threshold impacts is correct, then the chance of an asteroid catastrophe happening in the near future — while very low — is greater than the probability of other threats to life that our society takes very seriously. For purposes of discussion, we adopt a once-in-500,000-year estimate for the globally catastrophic impact. It is important to keep in mind that the frequency could be greater than this, although probably not by more than a factor of ten. The frequency could equally well be a factor of ten smaller.

Because the risk of such an impact happening in the near future is very low, the nature of the impact hazard is unique in our experience. Nearly all hazards we face in life actually happen to someone we know, or we learn about them from the media, whereas no large impact has taken place within the total span of human history. (If such an event took place before the dawn of history roughly 10,000 years ago, there would be no record of the event, since we are not postulating an impact nearly large enough to produce a mass extinction that would be readily visible in the fossil record). But also in contrast to more familiar disasters, the postulated impact would produce devastation on a global scale. Natural disasters, including tornadoes and cyclones, earthquakes, tsunamis, volcanic eruptions, firestorms, and floods often kill thousands of people, and occasionally several million. But the civilization-destroying impact exceeds all of these other disasters in that it could kill a billion or more people, leading to as large a percentage loss of life worldwide as that experienced by Europe from the Black Death in the 14th century. It is this juxtaposition of the small probability of occurrence balanced against the enormous consequences if it does happen that makes the impact hazard such a difficult and controversial topic.

2.4.1 Frequency of impacts of different sizes

We begin to address the risk of cosmic impacts by looking at the frequency of events of different magnitudes. Small impacts are much more frequent than large ones, as is shown in Fig. 2-4. This figure illustrates the average interval between impacts as a function of energy, as derived from the lunar cratering record and other astronomical evidence. For purposes of discussion, we consider two cases: the threshold globally catastrophic impact discussed above, and for comparison, a Tunguska-class impact from a smaller object perhaps 100 m in diameter. In all of the examples given below, the numbers are approximate and are used only to illustrate the general magnitudes involved.

For the globally catastrophic impact:

- Average interval between impacts: 500,000 years

For the Tunguska-class impacts:

- Average interval between impacts for total Earth: 300 years
- Average interval between impacts for populated area of Earth: 3,000 years
- Average interval between impacts for world urban areas: 100,000 years
- Average interval between impacts for U. S. urban areas only: 1,000,000 years

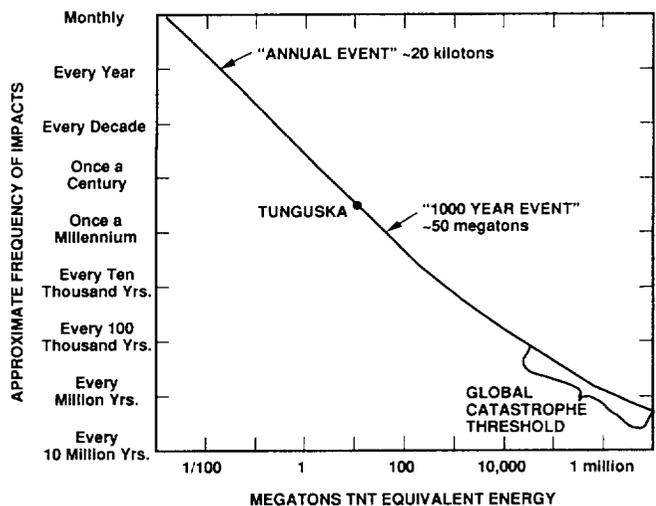


Figure 2-4. *Estimated frequency of impacts on the Earth from the present population of comets and asteroids, and evidence from lunar craters. The megaton equivalents of energy are shown, as are possible and nearly certain thresholds for global catastrophe. (based on Shoemaker 1983)*

We see from this simple calculation that even for a large, urbanized country such as the U. S., the Tunguska-class impacts on metropolitan areas occur less often than the globally catastrophic impact, emphasizing the fact that the large impacts dominate the risk. This point is also made in Fig. 2-5, which plots the expected fatalities per event as a function of diameter (and energy) of the impacting object. The figure shows schematically the transition in expected fatalities per impact event that takes place as the global threshold is reached for objects between 0.5 and 5 kilometers in diameter.

2.4.2 Annual risk of death from impacts

One way to address the risk is to express that risk in terms of the annual probability that an individual will be killed as a result of an impact. This annual probability of mortality is the product of (a) the probability that the impact will occur and (b) the probability that such an event will cause the death of any random individual.

For the globally catastrophic impact:

- Average interval between impacts for total Earth: 500,000 years
- Annual probability of impact: 1/500,000
- Assumed fatalities from impact: one-quarter of world population
- Probability of death for an individual: 1/4
- Annual probability of an individual's death: 1/2,000,000

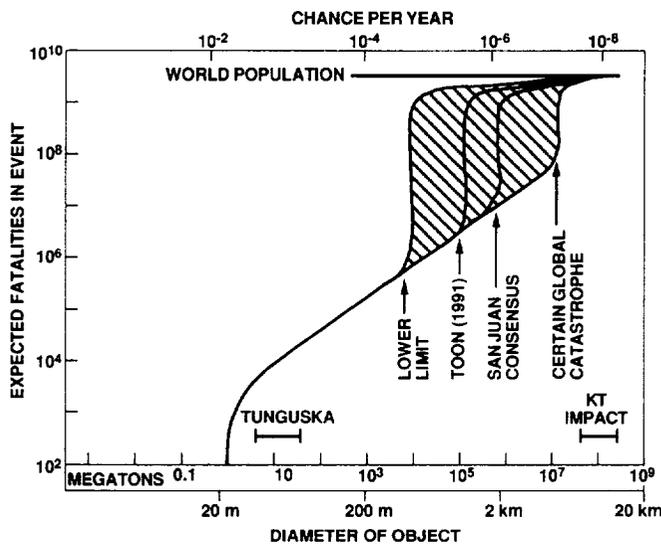


Figure 2-5. Large impacts dominate the risk, as seen in this schematic indication of expected fatalities per event as a function of diameter (and energy) of the impacting object. (C. Chapman)

For the Tunguska-class impact:

- Average interval between impacts for total Earth: 300 years
- Assumed area of devastation and total mortality from impact: 5,000 sq km (1/10,000 of Earth's surface)
- Annual probability of an individual's death: 1/30,000,000

Thus we see that the annualized risk is about 15 times greater from the large impact than from the Tunguska-class impact.

2.4.3 Equivalent annual deaths as a measure of risk

An alternative but equivalent way to express the risks is in terms of average annual fatalities. While such an index is convenient for comparison with other risks, we stress the artificiality of applying this approach to the very rare impact catastrophes. The concept of equivalent annual deaths strictly applies only to averages over long periods of time in a static world in which the population and the mortality rate from other causes do not vary with time. This figure is obtained by multiplying the population of the Earth by the total annual probability of death calculated above. In the case of the U. S.-equivalent deaths, we allow for the higher-than-average population density in the U. S.:

For the globally catastrophic impact:

- Total annual probability of death: 1/2,000,000
- Equivalent annual deaths for U. S. population only: 125
- Equivalent annual deaths (worldwide population): 2,500

For the Tunguska-class impact:

- Total annual probability of death: 1/30,000,000
- Equivalent annual deaths for U. S. population only: 15
- Equivalent annual deaths (worldwide population): 150

These figures can be compared with the mortality rates from other natural and human-made causes to obtain a very rough index of the magnitude of the impact-catastrophe hazard. For example, the U. S. numbers can be compared with such other causes of death as food poisoning by botulism (a few per year), tornadoes (100 per year), and auto accidents (50,000 per year).

2.4.4 Qualitative difference for the impact catastrophe

The above analysis is presented to facilitate comparison of impact hazards with others with which we may be more familiar. However, there is a major *qualitative* difference between impact catastrophes and other more common natural disasters. By definition, a global impact catastrophe would lead to a billion or more fatalities and an end to the world as we know it. No other natural disasters, including the much-smaller Tunguska-class impacts, have this nature. They represent just one among many causes of human death. In contrast, the potential consequences of a large impact set it apart from any other phenomenon with the exception of full-scale nuclear war.

2.5 CONCLUSIONS

The greatest risk from cosmic impacts is associated with asteroids a few kilometers in diameter; such an impact would produce an environmental catastrophe that could lead to more than a billion fatalities. We do not know the threshold diameter at which the impact effects take on this global character, but it is probably near 2 km, and it is unlikely to be less than 1 km. As a first step toward significant reduction of this hazard, we need to identify potential asteroidal impactors larger than 1 km diameter. In addition,

attention should be given to the inherently more difficult problem of surveying as many potential cometary impactors of similar equivalent energy as is practical. As noted in Chapter 5, the comets account for 5 to 10 percent of impactors in this size range. However, because of their greater impact speeds, these comets could contribute as much as 25 percent of the craters larger than 20 km in diameter.

Finally, because of the higher frequency and nonetheless significant consequences of impact of objects with diameters in the range of 100 m to 1 km, the survey should include bodies in this size range as well. There are wide differences among people in their psychological and political responses to hazards of various types. We have concentrated on the globally catastrophic case because of its qualitatively dreadful nature. But some people consider the threat of the more frequent Tunguska-like events to be more relevant to their concerns, even though the objective hazard to human life is less. To protect against such events (or at least mitigate their effects), impactors as small as 100 m diameter would need to be located with adequate warning before impact to destroy them or at least evacuate local populations. As described in Chapter 7, the survey network designed to detect and track the larger asteroids and comets will also discover tens of thousands of Earth-approaching objects in the 100-m to 1-km size range.

CHAPTER 3

THE NEAR-EARTH-OBJECT POPULATION

3.1 INTRODUCTION

There are two broad categories of objects with orbits that bring them close to the Earth: comets and asteroids. Asteroids and comets are distinguished by astronomers on the basis of their telescopic appearance. If the object is star-like in appearance, it is called an asteroid. If it has a visible atmosphere or tail, it is a comet. This distinction reflects in part a difference in composition: asteroids are generally rocky or metallic objects without atmospheres, whereas comets are composed in part of volatiles (like water ice) that evaporate when heated to produce a tenuous and transient atmosphere. However, a volatile-rich object will develop an atmosphere only if it is heated by the Sun, and an old comet that has lost much of its volatile inventory, or a comet that is far from the Sun, can look like an asteroid. For our purposes, the distinction between a comet and an asteroid is not very important. What matters is whether the object's orbit brings it close to the Earth — close enough for a potential collision.

The most useful classification of NEOs is in terms of their orbits. The near-Earth asteroids are categorized as Amors, Apollos, and Atens, according to whether their orbits lie outside that of the Earth, cross that of the Earth with period greater than 1 year, or cross that of the Earth with period less than 1 year, respectively (see the Glossary for precise definitions of these and other technical terms). Another class of NEO, consisting of asteroids and comets whose orbits lie entirely within the orbit of Earth, doubtless exist, although no such objects are currently known. Cometary objects are classed as short period if their periods are less than 20 years, intermediate period if their periods are between 20 and 200 years, and as long period if their periods are greater than 200 years.

Even more relevant to this report is the definition of an Earth-crossing asteroid (ECA). These are the asteroids that have the potential to impact our planet. An ECA is defined rigorously (Helin and Shoemaker, 1979; Shoemaker, 1990) as an object moving on a trajectory that is capable of intersecting the capture cross-section of the Earth as a result of on-going long-range gravitational perturbations due to the Earth and other planets. In this case "long-range" refers to periods of tens of thousands of years. For any particular NEO, it will not be clear whether it is in fact an ECA until an accurate orbit is calculated. Thus the concept of an ECA does not apply to a newly discovered object. Ultimately, however, it is only ECAs that

concern us in a program aimed at discovering potential Earth impactors. In an analogous way, we define Earth-crossing comets (ECCs) as intermediate- and long-period comets with orbits capable of intersecting the capture-cross-section of the Earth.

3.2 ASTEROIDS AND COMETS IN NEAR-EARTH SPACE

In 1989 there were 90 known ECAs (Shoemaker 1990), while 128 ECAs were known at the time this Workshop convened in June 1991 (Appendix A). None of them is today a hazard, since none is currently on an orbit that permits collision with the Earth. But all of them are capable of evolving into Earth-impact trajectories over the next few thousand years. And, in fact, it is estimated that 20 to 40 percent of the ECAs will ultimately collide with our planet (Wetherill, 1979; Shoemaker and others, 1990). The others will either be ejected from the inner solar system through a close encounter with the Earth or will impact or be ejected through close encounters with the planets before they reach the Earth.

The 128 known ECAs are comprised of 11 Atens (9 percent), 85 Apollos (66 percent), and 32 Earth-crossing Amors (25 percent). Sixty-one of these have received permanent catalog numbers, implying their orbits are well established, while moderately reliable orbits are in hand for 51 others. The remaining 16 are considered lost, meaning their orbits are not well enough known to predict the current locations of these bodies. Further observations of them will occur only through serendipitous rediscovery.

All ECAs brighter than absolute magnitude 13.5 are believed to have been discovered. (The absolute magnitude is defined as the apparent magnitude the object would have if it were 1 Astronomical Unit (AU), or 150 million kilometers, from both the Earth and Sun). Translated to sizes, this means all ECAs larger than 14 km have been detected for the case of low reflectivity (dark) bodies, such as C-class asteroids. The limiting diameter is about 7 km for more reflective objects, such as S-class asteroids. We estimate that about 35 percent of the ECAs having absolute magnitudes brighter than 15.0 (6 and 3 km diameters, respectively, for the dark and bright cases) have been discovered. At absolute magnitude 16 (4 and 2 km), the estimated completeness is only 15 percent, while at absolute magnitude 17.7 (2 and 1 km), it is only about 7 percent. The largest ECAs are 1627 Ivar and 1580 Betulia, each with diameter of about 8 km, or slightly smaller than the object whose impact ended

the Cretaceous period. The smallest ECAs yet discovered are 1991 BA, an object that passed within 0.0011 AU (one-half the distance to the Moon) in January 1991, and 1991 TU, which passed within 0.0049 AU in October 1991; both have diameters of about 10 m.

Based on search statistics and the lunar cratering record, we estimate that the populations of Earth-crossing asteroids and comets can be approximated by several power laws, which reflect a general exponential increase in the numbers of NEOs as we go to smaller and smaller sizes. Each segment of the distributions can be described, mathematically, as follows, where N is larger than a given diameter D :

$$N = k D^b$$

where k is a constant and b is the power-law exponent. Although the general form of the size distributions for asteroids and comets is demonstrated by observations, the detailed distributions are not accurately known. The simulations that will be described in subsequent chapters require models for the asteroid and comet populations, however. For our ECA population model, we estimate that changes in the power law occur at diameters of 0.25 and 2.5 km, and have adopted exponents of -2.6 ($D \leq 0.25$ km), -2.0 (0.25 km $< D \leq 2.5$ km), and -4.3 ($D > 2.5$ km).

Estimates for the total number of asteroids having diameters larger than values of particular interest are shown in Fig. 3-1 by the solid curve. Specific population estimates at sizes of interest are indicated in the figure, where our uncertainties are bounded by the dashed lines. For example, we estimate there are 2,100 ECAs larger than 1 km in diameter, with an uncertainty of a factor of two.

Active comets can also cross the Earth's orbit with the potential for collision. From Everhart's (1967) determination of cometary orbits, it can be inferred that 10 to 20 percent of all short-period comets are Earth-crossing. Using this fraction and the size-frequency distribution of short-period comets derived by Shoemaker and Wolfe (1982), we estimate that the population of short-period comets having Earth-crossing orbits is likely to comprise about 30 ± 10 objects larger than 1 km diameter, 125 ± 30 larger than 0.5 km diameter, and 3000 ± 1000 larger than 0.1 km diameter. Comparing these numbers with those for the ECA population in Fig. 3-1 shows that at any given size, short-period comets contribute only an additional 1 percent or so to the total population. This contribution is negligible compared to the estimated uncertainty in the ECA population. As stated previously, an object that displays no apparent atmosphere or tail is classified as an asteroid even if its orbital properties are similar to that of a short-period comet. Dormant or extinct short-period comet nuclei are

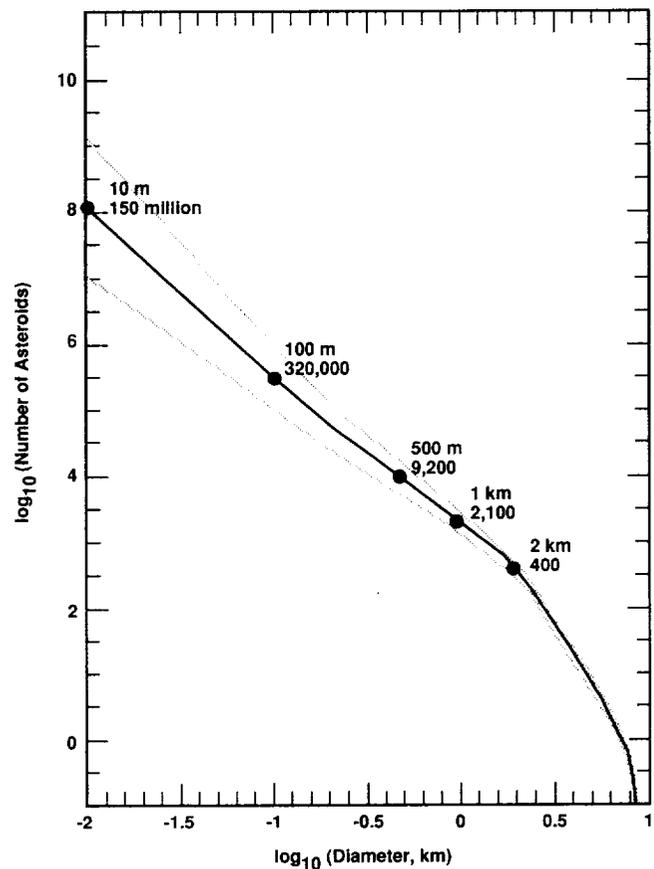


Figure 3-1. Estimated number of Earth-crossing asteroids larger than a given diameter (E. Bowell).

therefore likely members of the ECA population, and such objects are implicitly included in the ECA estimates given above.

Although about 700 long-period comets are known to have passed through the inner solar system during recorded history, their total population is difficult to characterize. Only about half of these comets had Earth-crossing orbits and thus can be termed ECCs, where we define a comet to be an ECC if it has period greater than 20 years and a perihelion less than 1.017 AU. Fernández and Ip (1991) estimate a flux of about three ECCs brighter than absolute magnitude of 10.5 per year. From work by Weissman (1991), we estimate these bodies to be between 3 and 8 km in diameter. From their orbital and size distributions, we estimate that ECCs are about five times more abundant than Earth-crossing short-period comets. Thus the total number of ECCs is only about 5 to 10 percent that of the ECA population. As noted previously, however, the long-period comets contribute disproportionately to the impact flux because of their higher impact speeds relative to those of the asteroids. Indeed, we estimate that they contribute about 25 percent of the total NEO hazard. To model the flux of ECCs that move inside the Earth's orbit, we assume

a power-law distribution of $180 D^{(-1.97)}$ per year. This flux appears to be two or three times larger than others have estimated because our model associated a larger nucleus diameter with a given apparent brightness, but the predicted number of ECCs of a given brightness should remain unaffected.

3.3 ORIGIN AND FATE OF NEOs

Near-Earth objects are efficiently removed from the solar system by collisions or gravitational interactions with the planets on time-scales of 10 to 100 million years. Thus the NEO population we see today must be continually resupplied, as any remnant primordial population would have long been depleted. This process of depletion has had consequences for the geological evolution of the terrestrial planets, as evidenced by the existence of large craters. Removal of NEOs by impacts has profound consequences for biological evolution on Earth.

As the basis for understanding the origin of NEOs is the need to identify their source of resupply (Wetherill, 1979). Cometary objects appear to be supplied from either the very distant reservoir called the Oort cloud or the somewhat closer disk called the Kuiper belt, which have preserved unprocessed (unheated) material from the time of the solar system's formation. The great age and primitive chemistry of comets make their study vital to our understanding of planetary accretion and chemistry. Galactic tidal effects and random gravitational perturbations from passing stars or molecular clouds can alter the orbits of Oort cloud members, causing some of them to make a close approach to the Sun. Although the comets initially have long orbital periods, they can be perturbed into short-period orbits through interactions with Jupiter and the other planets.

Two sources have been hypothesized for supplying asteroidal NEOs, both with profound implications on our understanding of solar system evolution. The first hypothesis is that they are derived from main-belt asteroids through the process of collisions and chaotic dynamics. It has been shown that objects orbiting in a 3:1 mean motion resonance with Jupiter (the location of one of the "Kirkwood Gaps" at 2.5 AU) exhibit chaotic increases in their orbital eccentricity, allowing their orbits to cross those of the terrestrial planets. In addition to the dynamical calculations that support this hypothesis, observational evidence shows that many NEOs are compositionally similar to main-belt asteroids. In many ways, they seem to resemble the smaller main-belt asteroids, and both theory and observation support the hypothesis that both groups consist primarily of fragments generated in occasional collisions between main-belt asteroids.

A second proposed source for NEOs is from dormant or extinct comet nuclei. The end stages of a comet's life are poorly understood; one scenario is that as surface volatiles are depleted, an inert mantle forms which effectively seals off and insulates volatiles within the interior. Without the presence of an atmosphere or tail, such a body would have an asteroidal appearance. Observational evidence that supports this hypothesis includes several asteroidal NEOs that have orbits similar to known short-period comets. At least one of the cataloged asteroids, 3200 Phaethon, is known to be associated with a strong meteor stream (the Geminids). Previously, strong meteor streams were known to be associated only with active comets. Further, the orbits of some asteroidal NEOs do not appear to follow strict gravitational dynamics, suggesting the action of some non-gravitational forces such as those associated with cometary activity.

3.4 PHYSICAL PROPERTIES OF NEOs

The physical and compositional nature of asteroids and comets is inferred from telescopic observations aided by comparisons with the meteorites. Most meteorites appear to be fragments of asteroids, and in many cases it is possible to match the reflectance spectra of individual asteroids with those of meteorites measured in the laboratory (Fig. 3-2). Most of this work has been done for the main-belt asteroids, however, since the near-Earth asteroids are generally faint and must be observed within a rather narrow window of accessibility.

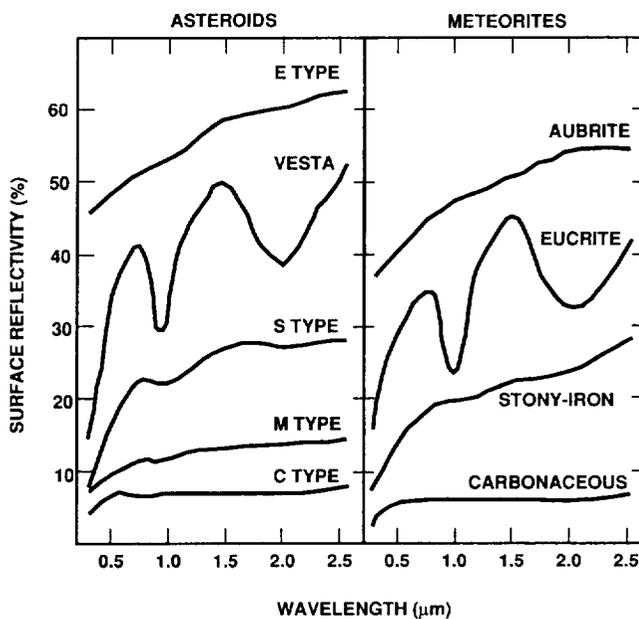


Figure 3-2. Comparison of the spectral reflectance of asteroids and meteorites (C. Chapman).

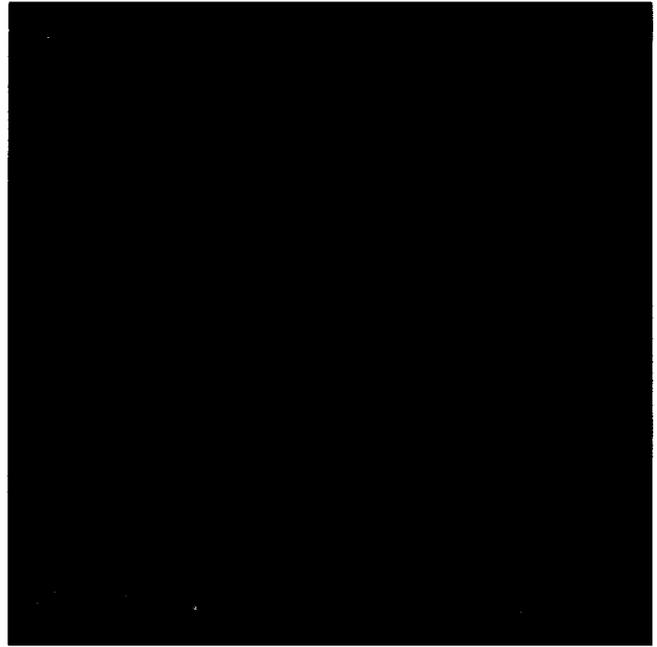


Figure 3-3. The Apollo asteroid 4769 Castalia is shown in the discovery photo at left taken on August 9, 1989 using the 0.46-m Schmidt telescope at the Palomar Observatory. Quick alerts allowed follow-up by radar observations (right) on August 22 at Arecibo, Puerto Rico. Radar images revealed the asteroid's two-lobed form and its four-hour rotation rate. (Photographs courtesy of (left) E. F. Helin (Caltech/JPL), Planet-Crossing Asteroid Survey; (right) S. Ostro (Caltech/JPL).

Although most known Earth-approaching asteroids have never been observed for physical properties, and those that have been are generally only poorly observed relative to the brighter main-belt asteroids, some things can be said about them. They exhibit a diversity in inferred mineralogy approaching that in the rest of the asteroid population. The majority are expected to be similar to the dark C-type asteroids in general properties (presumably moderately low-density, volatile-rich bodies, colored black due to at least several percent of opaque material). There are also a large number of S-types. (S-types are thought to be either stony, chondrite-like objects, stony-iron objects, or a combination of both.) In addition, there are known examples of metallic bodies (probably like nickel-iron alloy meteorites) and basaltic bodies.

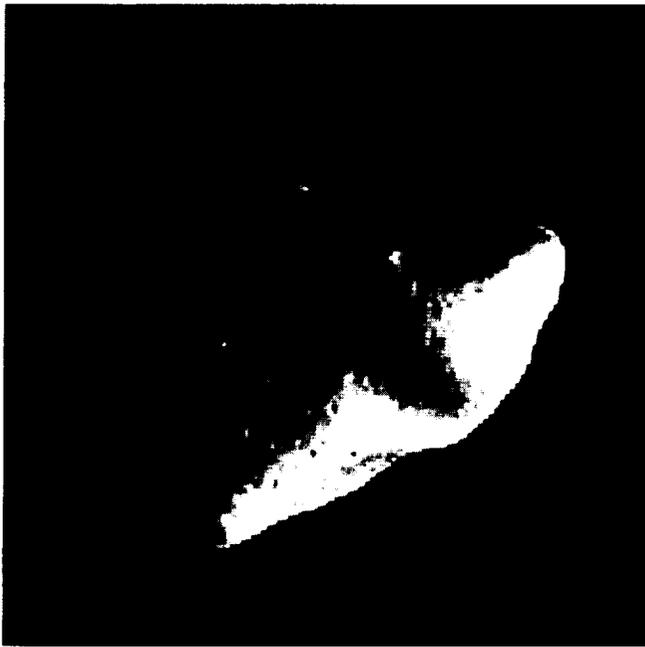
These asteroids are small and often quite irregular in shape; they also tend to have rather rapid spins, but there is a great diversity in such properties. Their densities have not been measured, but are inferred to be typical of rocky material (about 2 to 3 g/cm³). In only one case has an Earth-approaching object been imaged: 4769 Castalia (Fig. 3-3). Remarkably, the radar image shows a highly elongated object that may be a contact binary composed of two objects of comparable size. Although astronomers have presumed that these objects are coherent, intact bodies like large boulders, it is possible that some or many of

them are aggregates, like rubble piles, which may have little or no internal cohesion.

Only one asteroid has been investigated by a spacecraft: in October 1991, the Jupiter-bound Galileo spacecraft passed within 1,600 km of the main-belt asteroid 951 Gaspra (Fig. 3-4). Gaspra, an irregularly shaped S-type asteroid, is slightly larger than the largest known ECAs.

It is particularly uncertain what the physical properties of comets (dead or alive) might be like. Only one comet has been studied in detail: Comet Halley, which was the target of several flyby spacecraft missions at the time of its last apparition in 1986. The nucleus of Halley (Fig. 3-5) is irregular and dark, with an average diameter of about 10 km. Like other comets, it is made of a combination of ice(s), rocks, and dust. Much of the atmospheric outgassing near the Sun is confined to discrete plumes or jets. In general, the physical configuration of comets is even less well understood than that of the small asteroids, and many comets have been observed to split under rather modest tidal and thermal forces. Their densities have not been measured but are thought to be about 1 g/cm³, although many different estimates can be found in the scientific literature on comets. If we assume that comets are homogeneous and have roughly the same composition as Halley, then cometary nuclei are about half non-volatiles and half ices by volume. The non-volatiles include both silicates and organic mate-

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NASA/Jet Propulsion Laboratory

Figure 3-4. 951 Gaspra, an S-type main-belt asteroid, was imaged by the Jupiter-bound Galileo spacecraft on October 29, 1991 from a distance of about 16,200 km. Gaspra is an irregularly shaped object measuring about 18x11x10 km. It is the only asteroid yet studied by a spacecraft.



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Figure 3-5. The nucleus of Comet Halley, as seen from the European Space Agency's Giotto spacecraft.

rials. The primary ices (with percentages derived for Halley) are water (80 percent) and carbon monoxide (15 percent), plus lesser quantities of formaldehyde, carbon dioxide, methane, and hydrocyanic acid.

The relationships among the brightness of comets, the size of their solid nuclei, and their distance from the Sun are complex and not fully understood. Two comets with known nuclear sizes (both about 10 km diameter), Halley and IRAS-Araki-Alcock, differed by more than a factor of 100 in intrinsic brightness when near 1 AU from the Sun. Each well-observed intermediate- or long-period comet has exhibited a different pattern of activity as it approached and retreated from perihelion. Indeed, periodic comets exhibit different patterns of activity on different returns. Though seldom observed at solar distances greater than 5 AU, most long-period comets evidently become active somewhere between 5 and 10 AU.

For a study of impacts, it is not essential to know a great deal about the physical nature of comets and

asteroids. The most important properties are simply their mass and impact velocity, although it would make a difference if the projectile were double or multiple and easily came apart as it entered the atmosphere. Any future program for intercepting and diverting an incoming comet or asteroid will require detailed knowledge of the configuration, density, cohesion, and composition of these objects. For these reasons, in addition to their significance for basic science, spacecraft missions to comets and near-Earth asteroids are essential. The first opportunity for a detailed study of a comet is provided by the NASA Comet Rendezvous and Asteroid Flyby mission (CRAF), now planned to study Comet Kopff in 2006-09. The opportunity for a similar study of a near-Earth asteroid will depend on approval of the NASA Discovery program of small planetary missions, the first of which is to be a rendezvous with a near-Earth asteroid.

CHAPTER 4

HISTORY AND CURRENT PROGRAMS

4.1 INTRODUCTION

The first recognized Earth-crossing asteroid, Apollo, was discovered photographically in 1932 at Heidelberg and then lost until 1973. In the following decades only a handful of additional ECAs were discovered, and many of these were temporarily lost also. Not until the 1970s was a regular search initiated, using a wide-field Schmidt telescope of modest aperture. Several expanded photographic survey programs continue today with steadily increasing discovery rates. In the early 1980s these photographic approaches were supplemented by a new technique of electronic CCD scanning implemented at the University of Arizona, and by the late 1980s this more automated approach was also yielding many new discoveries. Even today, however, the total worldwide effort to search for NEOs amounts to fewer than a dozen full-time-equivalent workers, a number of whom are volunteers! In this chapter we briefly review the history and current status of both the photographic and CCD searches.

4.2 PHOTOGRAPHIC SEARCH PROGRAMS

The overwhelming majority of discoveries of near-Earth asteroids (and increasingly of comets) has been obtained from photographic searches carried out with wide-field Schmidt telescopes. The bulk of discoveries have been made in the last decade, and the rate of discovery is rapidly increasing. This increase is due in part to improved technology but principally to increased interest within the astronomical community.

To date the two most productive photographic teams in this field have been those directed by E. F. Helin and E. M. Shoemaker. Most of their work has been done using the 0.46-m Schmidt telescope at Palomar Observatory, California. Observing programs on three large Schmidt telescopes located in France, Chile, and Australia have also contributed but rather sporadically, as has work carried out with a narrower-field astrograph in Ukraine. A new successful program has recently been started on the U. K. Schmidt in Australia. The three main photographic programs now in operation are described briefly below.

Various techniques are used to detect and measure NEOs, but the search process must be carried out very soon after the exposure in order to permit rapid follow-up. In some programs the films are exposed in pairs with a gap in time between the first and subsequent exposure, then scanned with a specially built stereo comparator. Images that move noticeably

between the first and second exposure may be detected in this way. Alternatively, a visual search can be carried out using a binocular microscope, and trailed images (produced by the motion of the NEO during the time exposure) are noted. The angular velocity may be inferred from the motion between exposures or, in the case of a single exposure, from the trail length (Fig. 4-1). Selection of potential NEOs is carried out on the basis of this angular velocity, and only those objects with anomalous motions are followed up to determine precise orbits.

A variety of photographic emulsions have been used in NEO searches, but the most effective have been the IIIa-type emulsions coated on glass from Kodak, introduced twenty years ago, and a panchromatic emulsion coated on a film base released in 1982, again from Kodak. The new film (4415) has been particularly useful and is now the emulsion of choice for this work.

Planet-Crossing Asteroid Survey (PCAS)

The PCAS survey for Earth-crossing and other planet-crossing asteroids was initiated by E. F. Helin and E. M. Shoemaker in 1973 and is now directed by

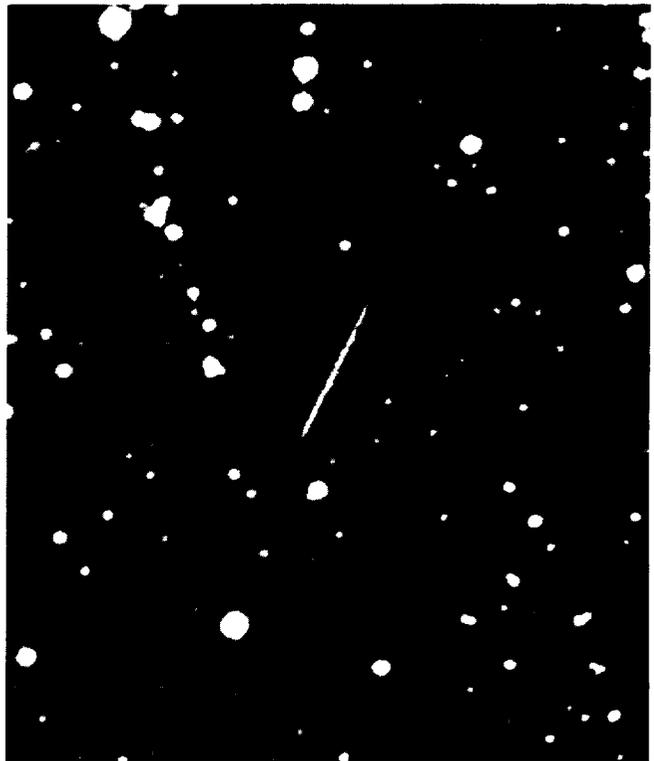


Figure 4-1. 2062 Aten, discovered in January 1976, was the first asteroid found with an orbit smaller than Earth's orbit, and is the prototype of Aten asteroids. (E. F. Helin)

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Helin (Helin and Shoemaker, 1979; Helin and Dunbar, 1984, 1990). It is the longest-running dedicated search program for the discovery of near-Earth asteroids and is carried out with the 0.46-m Schmidt telescope at Palomar Observatory in California. Early in the survey, about 1,000 square degrees of sky were photographed each month. In the last ten years, the use of fast film has allowed shorter exposures leading to greater sky coverage. This fact, in combination with a custom-made stereo-microscope, has resulted in a five-fold increase in the discovery rate over the early years of the program. Using the stereo pair method, up to 4,000 independent square degrees of sky can be photographed per month. This program has been particularly successful in getting out early alerts on new discoveries so physical observations can be obtained at other telescopes during the discovery apparition. There has also been an organized international aspect to this program, called the International Near-Earth Asteroid Survey (INAS), which attempts to expand the sky coverage and the discovery and recovery of NEAs around the world.

Palomar Asteroid and Comet Survey (PACS)

A second survey with the Palomar 0.46-m Schmidt was begun by E. M. and C. S. Shoemaker in 1982 and has continued with the collaboration of H. E. Holt and D. H. Levy (Shoemaker and others, 1990). About 3,000 square degrees of sky are photographed each month. Both the PACS and PCAS programs center their sky coverage at opposition and along the ecliptic and attempt to cover as much sky as possible in every seven-night observing run at the telescope. The two programs combined produce about 6,000 independent square degrees of sky coverage per month.

Anglo-Australian Near-Earth Asteroid Survey (AANEAS)

The AANEAS program began in 1990 under the direction of D. I. Steel with the collaboration of R. H. McNaught and K. S. Russell using a visual search of essentially all plates taken with the 1.2-m U. K. Schmidt Telescope as part of the regular sky survey (Steel and McNaught, 1991). Up to 2,500 square degrees are covered each month to a limiting stellar magnitude near 22.

4.3 THE SPACEWATCH CCD SCANNING PROGRAM

An alternative to photographic search programs was developed at the University of Arizona under the name "Spacewatch" by T. Gehrels in collaboration with R. MacMillan, D. Rabinowitz, and J. Scotti (Gehrels, 1991; Rabinowitz, 1991). This system makes use of a CCD detector instead of photographic plates. It differs from the wide-field Schmidt searches in scanning smaller areas of sky but doing so to

greater depth. In 1981, the Director of the University of Arizona Observatories made the Steward 0.9-m Newtonian reflector on Kitt Peak available, and initial funding for instrument development was obtained from NASA. By 1983 Spacewatch had a 320 x 512 pixel CCD in operation, which was too small for discovery of near-Earth asteroids on that telescope, but was exercised in order to get experience with CCD modes of operation. Later this was upgraded to a 2048x2048 pixel CCD.

The basic construction and operation of the CCD are ideal for scanning. We refer to the "scanning mode"; in older literature it is called Time Delay Integration (TDI). The scanning is done by exactly matching the rate of transfer of the charges, from row to row of the CCD chip, with the rate of scanning by the telescope on the sky. A basic advantage of scanning is the smooth continuous operation, reading the CCD out during observing, compared to a stop-and-go procedure resetting the telescope for each exposure and waiting for the CCD to be read out before the next exposure can be started. Another advantage of scanning is that the differences in pixel sensitivity are averaged out, and two-dimensional "flat fielding" calibration is therefore not needed.

As each line of the CCD image is clocked into the serial shift register, it is read out by the microcomputer and passed on to the workstation. There the data are displayed, searched for moving objects, and recorded on magnetic tape. As each moving object is discovered (Fig. 4-2), from the three repeated scan regions of about 30 minutes length, its image is copied to a separate "gallery" window for verification by the observer. Some five years of computer programming went into this system.

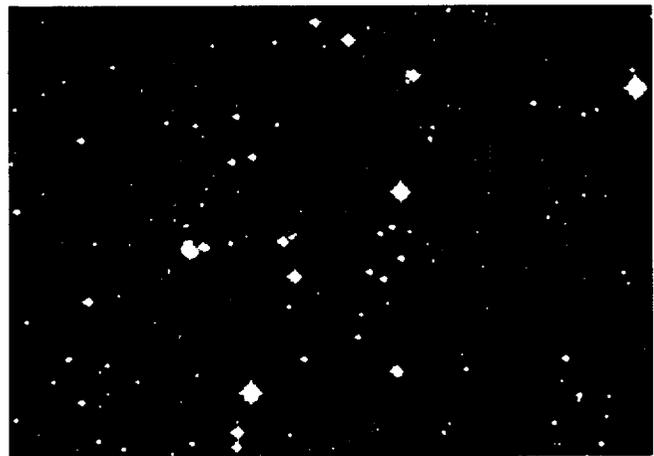


Figure 4-2. *Discovery image of near-Earth asteroid 1990 SS, discovered on September 25, 1990 by the Spacewatch CCD-scanning system. A main-belt asteroid is on the left and the faster-moving 1990 SS is on the right. The bright squares in each case indicate the positions on the previous two scans.*

Currently this Spacewatch system is discovering approximately as many NEOs as the photographic surveys. As a consequence of its more sensitive detector, it also tends to discover more smaller objects, including three objects found in 1991 that are only about 10 m in diameter. Substantial increases in capability are proposed with a new telescope of larger aperture (1.8 m) to replace the current Spacewatch telescope in the same dome.

4.4 POTENTIAL OF CURRENT PROGRAMS

Later chapters of this Report describe a survey program based on a new generation of scanning telescopes. However, there is still excellent work to be done with current instruments during the transition to the new survey. The near-term potential of photographic techniques may be considered in the following context. With the provision of about \$1 million capital costs and \$1 million per year operating expenses it would be possible to boost the current worldwide photographic discovery rate by at least a factor of two. Similarly, an upgrade of the Spacewatch CCD scanning system to 1.8-m aperture would more than double the output of this system, and still greater gains are possible utilizing advanced, large-format CCDs. This instrument can also be used as a test-bed for new NEO

survey techniques such as use of CCD arrays, optimizing of scanning strategies, and refinement of automated search software.

By the time large search telescopes with CCD detectors become available later in this decade it would be possible to have a sample of at least 1,000 NEOs with well-determined orbits. From this sample, which should include about 10 percent of the larger bodies, we will gain a much better idea of the physical properties and dynamical distribution of the total population. Such information will be invaluable in optimizing the search strategy of the large new telescopes. In addition, the operation of the large CCD search facilities will require trained personnel and a complex organization to utilize them to the fullest extent, and expansion of current programs can provide the experienced staff that will be required if and when the full survey begins operation.

We assume in the following facility overview that wide-field photography will continue in a substantially productive manner for a number of years. CCD work is expected at the Spacewatch telescope on Kitt Peak in Arizona (with proposed upgrade to 1.8-m aperture) and with the French OCA Schmidt and the Palomar 0.46-m Schmidt, both of which are proposed for conversion to CCD operation.

CURRENTLY ACTIVE AND POTENTIAL NEW PROGRAMS



PALOMAR OBSERVATORY, CALIFORNIA:

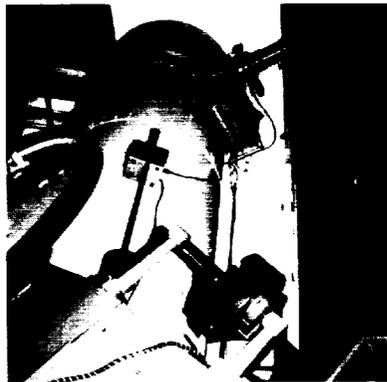
0.46-m Schmidt

This telescope is already highly productive as a photographic instrument, supporting both the PCAS and PACS programs described in the text. For continued photographic work, the main requirement is in the area of running costs and relatively straightforward instrumental additions. Plans are also underway to convert to CCD detectors.

PALOMAR OBSERVATORY, CALIFORNIA:

1.2-m Oschin Schmidt

This telescope, while currently dedicated to the new northern sky surveys, made significant contributions in the late '70s to mid '80s and has potential to make a significant contribution to asteroid searches; no specific plans for asteroid work are in place, however.



KITT PEAK OBSERVATORY, ARIZONA:

Spacewatch CCD Scanning Telescope

This telescope presently has 0.9-m aperture, with plans to upgrade to 1.8 m when funding is obtained. It is used for development of CCD scanning and data reduction techniques as well as the search for NEOs. The 2048x2048-pixel CCD, largest in the world, is seen in a liquid-nitrogen cooled dewar at the top, permanently mounted at the south Newtonian port.

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**LOWELL ANDERSON MESA OBSERVATORY,
ARIZONA: Perkins 0.4-m Schmidt**

This telescope exists but has not yet been installed at Anderson Mesa station. E. M. and C. S. Shoemaker hope to divide their time between this facility and Palomar if funds can be found to support its operation.

**SIDING SPRING, AUSTRALIA:
UK 1.2-m Schmidt**

The last year has seen a dramatic increase in the discovery rate from this telescope, now operated by the Anglo-Australian Observatory, and additional upgrades are planned for the near future. However, it does not provide for a comprehensive NEO search program of the sort being pursued at Palomar and Kitt Peak.

**SIDING SPRING, AUSTRALIA:
Uppsala 0.5-m Schmidt**

This telescope, owned by Uppsala Observatory, is currently used mainly for follow-up asteroid observations.

**EUROPEAN SOUTHERN OBSERVATORY,
CHILE: ESO 1.0-m Schmidt**

The survey work for which this telescope was constructed is now complete, and it may be available for NEO searches if suitably instrumented and funded.

**CERRO TOLOLO INTERAMERICAN
OBSERVATORY, CHILE: Curtis 0.6-m Schmidt**

Currently used for comet work, this telescope has recently been equipped with CCD detectors and could be used for some NEO searches or follow-up.

**CAUSSOLS, FRANCE:
OCA 1-m Schmidt**

Formerly called the CERGA Schmidt, this instrument is part of the Observatoire de la Côte d'Azur. Currently in limited use for NEO searches, this telescope is planned for conversion to CCD detectors in 1992, with a program aiming toward a 16-chip array to scan a band 8 degrees wide in the sky.

**CRIMEA, UKRAINE: Crimean Astrophysical
Observatory 0.4-m Astrograph**

NEOs have also been discovered using other photographic telescopes, notably with the 0.4-m astrograph of the Crimean Astrophysical Observatory in Ukraine. This instrument has been in use since 1963 in a study of faint main-belt asteroids, but it has also yielded several new NEOs.

CHAPTER 5

SEARCH STRATEGY

5.1 INTRODUCTION

It is feasible to conduct a survey for NEOs that will identify a large fraction of the asteroids and comets that are potentially hazardous to Earth (defined, for our purposes, as those that can come within about 0.05 AU, or about 20 times the distance to the Moon). Our objective in this chapter is to describe survey strategies that will identify a high percentage of potentially hazardous ECAs and short-period comets larger than 1 km diameter, and will provide advanced warning of the approach of hazardous long-period comets. This same survey will also yield many discoveries of smaller bodies, some of which are potential hazards on a local or regional basis.

A comprehensive survey requires monitoring a large volume of space to discover asteroids and comets whose orbits can bring them close to the Earth. Such bodies can be distinguished from main-belt asteroids by their differing motions in the sky and, in the case of comets, by visible traces of activity. To ensure reasonable levels of completeness, the volume within which we can find a 1-km or larger asteroid should extend as far as the inner edge of the main asteroid belt. Such a search could be carried out in the visible or infrared part of the spectrum, using telescopes on the Earth or in space. The analysis in this chapter is directed toward detection of the visible sunlight reflected from these NEOs, with no distinction made between telescopes on the ground or in orbit. However, since the least expensive option — ground-based astronomical telescopes with CCD detectors — is capable of meeting our survey requirements, we recommend this simple and cost-effective approach.

In this chapter we define a search strategy and use computer modeling to explore its quantitative implications. In Chapter 6 we describe the follow-up observations required to refine the orbits of newly discovered objects, and in Chapter 7 we present a proposed plan for an international network of survey telescopes to carry out this program.

5.2 POPULATION STATISTICS OF NEOS

To develop a quantitative survey strategy, we begin with the model for the Earth-approaching asteroids and comets that was described in Chapter 3. Although only a small fraction of these near-Earth asteroids and comets is now known, we have sufficient information to characterize the population for purposes of search simulation.

5.2.1 Asteroids

We have used the set of 128 known ECAs (Appendix A) in carrying out search simulations. Our objectives are defined in terms of discovery of these ECAs. This survey will also discover a large number of closely related Amor asteroids whose orbits will become Earth-crossing some tens or hundreds of millions of years in the future. The survey is also capable of discovering small main-belt asteroids, at a rate about 200 times greater than that of the ECAs.

The known ECA population is biased by observational selection (which tends to favor objects with orbits that bring them often into near-Earth space) and by the reflectivities of the bodies' surfaces (which favors the detection of bright objects over dark ones). Muinonen and others (1991) computed encounter velocities and collision probabilities of individual asteroids to correct for known sources of bias. The diameter distribution was approximated by a series of power laws, as described in Chapter 3. For our model simulation, there are 2,100 ECAs larger than 1 km diameter, 9,200 larger than 0.5 km, and 320,000 larger than 0.1 km. Of those larger than 0.5 km in diameter, about 3 percent are Atens, 85 percent are Apollos, and 12 percent are Earth-crossing Amors. Although the total population of ECAs larger than 1 km diameter is uncertain by as much as a factor of two (Fig. 3-1), the results of simulated surveys and the indications they provide about observing strategy should be qualitatively correct.

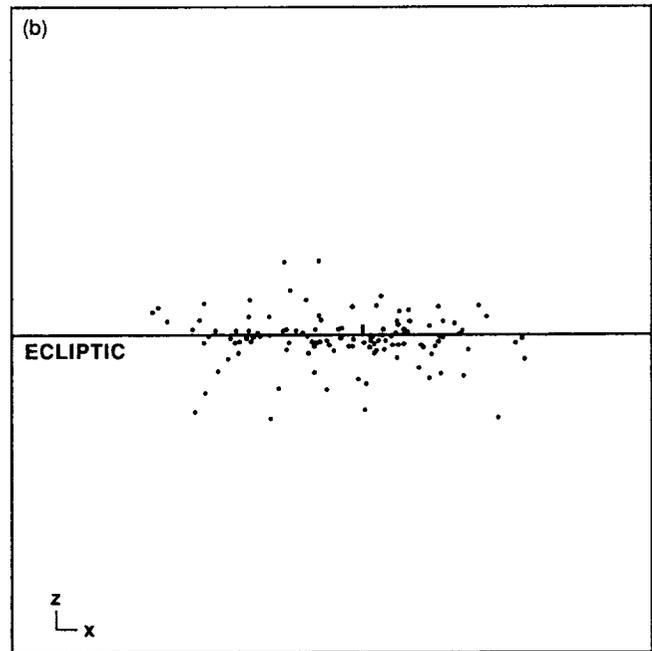
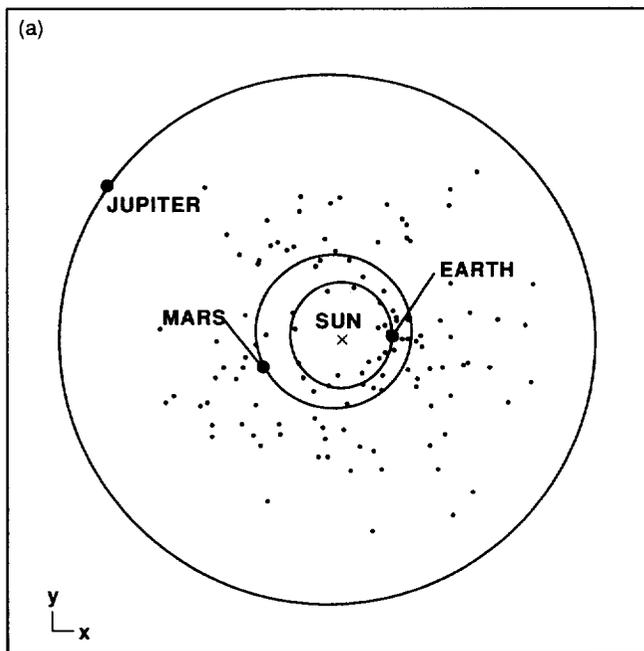
5.2.2 Comets

Since the orbits of short-period comets (those with periods less than 20 years) are rather similar to the ECAs, no special strategy need be devised to discover these comets. Indeed, the activity of most short-period comets makes them brighter and thus will enhance their discovery relative to ECAs of the same diameter. In what follows, the modeling of the discovery of ECAs should be taken to include that of short-period comets.

The intermediate- and long-period comets are quite different from short-period comets. For purposes of this report, we use the term ECC (Earth-crossing comet) for all comets having periods greater than 20 years and perihelion distances less than 1.017 AU. Because the majority of the ECCs discovered will make just one passage through the inner solar system during a survey of 25 years, they do not provide the repeated opportunities for discovery that exist for the ECAs. The best we can do is to identify incoming

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Art courtesy of E. Bowell and K. Muinonen

Figure 5-1. (a) Positions of known ECAs on 23 September 1991 in an ecliptic north pole projection of the inner solar system. The direction of the vernal equinox is to the right. Orbits and locations of Earth, Mars, and Jupiter are also shown. (b) Ecliptic plane projections of ECAs, on the same scale as (a). The ecliptic is shown as the horizontal line.

ECCs in time to give the longest possible warning time of their approach. For our simulations, we have used a sample of 158 ECCs observed during the last 100 years. We assume that the observations represent an unbiased sample of the true ECC population. According to this model, there are about 100 ECCs per year larger than 1 km diameter that pass within the orbit of the Earth.

In simulating the ECCs, we have also taken into account their activity (formation of an atmosphere), which causes them to brighten much more rapidly as they approach the Sun than would be expected from their size alone. The presence of an atmosphere enhances the detectability of comets, but the effect is not large until the comet comes inside the orbit of Jupiter, at which point we typically have only about one year warning.

5.3 SPATIAL AND SKY-PLANE DISTRIBUTIONS OF ECAs

Figure 5-1 shows the locations of the known ECAs on 23 September 1991 as seen from (a) north of the plane of the solar system and (b) as seen in that plane. About 10 percent are inside the Earth's orbit, and about 25 percent inside Mars'; these percentages should not vary much with time. Most of the ECAs are rather distant, the median geocentric distance being about 2.2 AU (where 1 AU is 150 million kilometers or about 375 times the distance to the Moon). Assuming practical observational limits of magnitude $V = 22$ and solar elongations greater than 75 deg (to be

discussed in greater detail below), about one-third of the known ECAs are observable from the Earth at any time.

The model population described above has been used to estimate the apparent or sky-plane distribution of ECAs (Muinonen and others, 1991). From Fig. 5-2, one expects a prevalence of detectable ECAs in the opposition and conjunction directions (that is, away from the Sun and toward the Sun). We also expect a concentration toward the ecliptic. The region near the Sun is not observable. These expectations are confirmed in Fig. 5-3, which shows instantaneous number-density contours of ECAs larger than 0.5 km diameter for limiting magnitudes $V = 18, 20,$ and 22 (note that larger magnitudes refer to fainter objects). Near opposition, and ignoring detection losses other than trailing produced by the apparent motion of the object, about 300 square degrees must be searched to $V = 18$ to be almost certain of detecting an ECA. To detect one at $V = 20$ we must search 50 square degrees, and 15 square degrees at $V = 22$.

5.4 MODELING WHOLE-SKY SURVEYS

To estimate the likely outcome of an ECA search program and to devise a sound observing strategy, Bowell and others (1991) used the model ECA population described above to simulate the results of 10-year surveys. Their results have since been expanded to include ECCs in the simulations described in this report. Factors investigated are: limiting search magnitude; search area and location; observing fre-

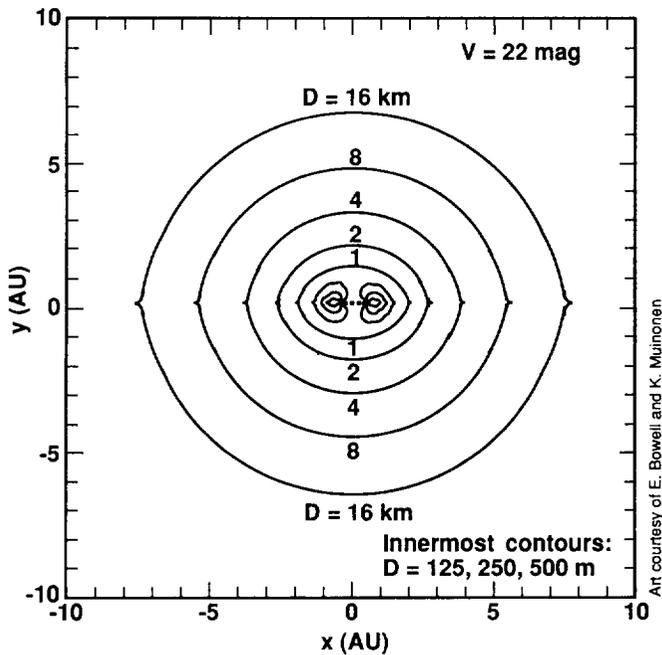


Figure 5-2. Detectability of dark C-class asteroids in the ecliptic plane as a function of diameter, assuming a magnitude limit $V = 22$. The effects of detection losses (see text) are not included. The origin of the coordinate system chosen is midway between the Earth and Sun, which are located at the ends of the dashed line.

quency; and survey duration. The simulations not only predict the percentage completeness of NEO discovery as a function of diameter, but they also impose requirements on instrumentation and software, suggest some of the necessary capabilities of a global network of observing stations, and give pointers on follow-up and orbit-determination strategy.

To model the expected rate of discovery of ECAs and ECCs, and to understand how a survey for ECAs can be optimized, we have allowed for the effects of detection losses — that is, of factors that cause some objects to be missed or that reduce the probability of their detection. These losses include trailing (as noted above), confusion with main-belt asteroids, and confusion with stars and galaxies. So-called “picket-fence” losses, which occur when an NEO eludes detection because of its rapid motion across regions being scanned, have not been included.

No survey can cover the entire sky because of interference from the Sun and Moon and other practical considerations. But as a reference, we calculate the fraction of NEOs discovered in a hypothetical whole-sky survey as a function of diameter, limiting magnitude, and survey duration. Figure 5-4 illustrates the results of ECA-survey simulations in which detection losses are allowed for and in which the whole sky is searched once each month. At a limiting magnitude of $V = 18$, comparable to the limit of the

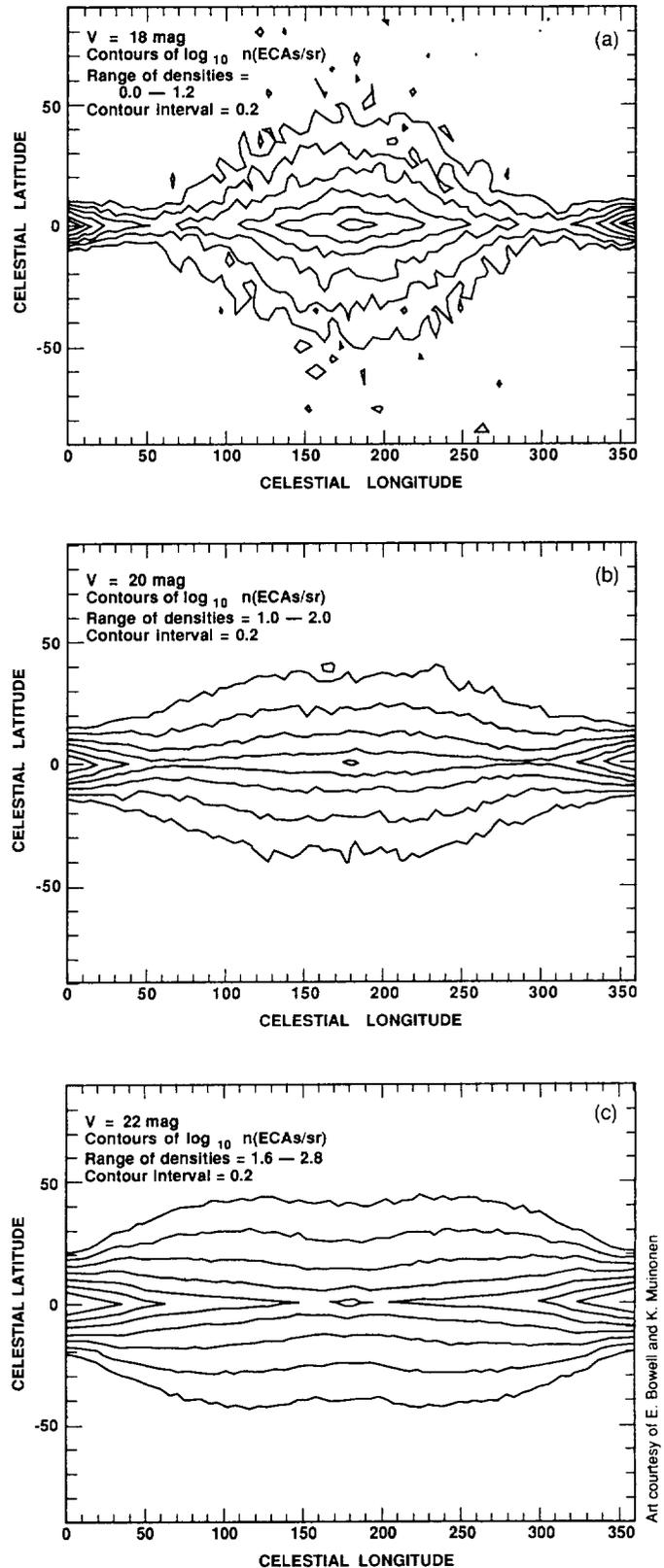


Figure 5-3. Modeled sky-plane number density of detectable ECAs larger than 0.5 km diameter for three limiting magnitudes: (a) $V = 18$, (b) $V = 20$, and (c) $V = 22$. Celestial longitude increases westward from conjunction (opposition is at longitude 180°). Contours of the logarithm of the number density of ECAs per steradian are shown at an interval of 0.2 over the ranges indicated. Note that regions near the Sun cannot be observed.

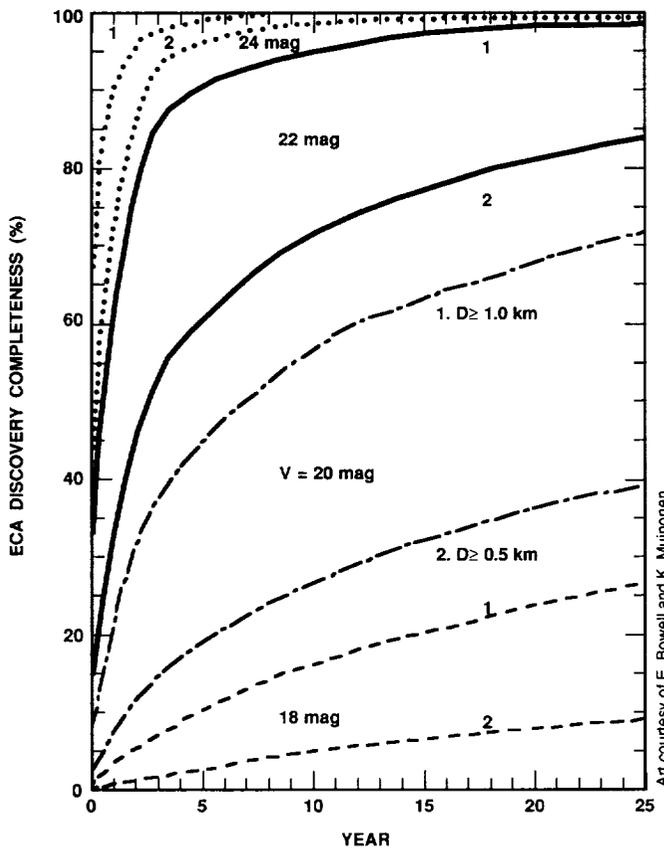


Figure 5-4. Discovery completeness of ECAs resulting from whole-sky surveys. Four curve types pertain, from the bottom, to surveys having limiting magnitudes $V = 18, 20, 22,$ and 24 mag. For each limiting magnitude, results for two diameter thresholds are shown: $D \geq 0.5$ and 1 km.

0.46-m Palomar Schmidt telescope currently used for several photographic surveys, even whole-sky surveys extending as long as 25 years yield only a small fraction of the largest ECAs. The problem is that the volume of space being searched is so small that many of the ECAs of interest simply do not pass through the volume being surveyed in a 25-year span. At $V = 20$, which is somewhat inferior to the current performance of the 0.9-m Spacewatch Telescope, fewer than half the ECAs larger than 1 km diameter are accessible in 15 years. To achieve greater completeness, and therefore greater levels of risk reduction, we must utilize larger telescopes with fainter limiting magnitudes, as will be described in Chapter 7.

At fainter magnitudes, much greater completeness is attainable, and discovery is characterized by a rapid initial detection rate followed after some years by a much slower approach to completeness. To survey, for example, 90 percent of ECAs larger than 1 km, a large area of the sky must be searched each month for a number of years to a magnitude limit of $V = 22$ or fainter. Because most of the large ECAs can be expected to be discovered early on, surveys lasting

many decades or even longer are mainly valuable for adding to the completeness of the discovery of smaller ECAs (less than 1 km diameter) and for continued monitoring of ECCs.

The ECCs spend almost all of their time in the outer solar system, and they can approach the inner solar system from any direction in space. They take about 16 months to travel from the distance of Saturn (9.5 AU from the Sun) to that of Jupiter (5.2 AU) and a little more than an additional year to reach perihelion. At any time, it is estimated that at least one thousand ECCs are brighter than $V = 22$ magnitude.

Modeling searches of the whole sky once a month for ECCs to magnitude limits of $V = 22$ and 24 reveals the shortness of the warning time even for faint limiting magnitudes. For $V = 22$, we would discover 93 percent of ECCs larger than 1-km diameter with three months warning time, but only 16 percent with one year warning time. For $V = 24$, the corresponding numbers would be 97 and 72 percent. For ECCs larger than 0.5 km, the discovery completeness would be 85 and 6 percent for $V = 22$, and 95 and 24 percent for $V = 24$.

From these numbers, it is clear that a high discovery percentage can only be achieved for warning times on the order of several months, even for a very deep limiting magnitude of $V = 24$. This result confirms our intuition that it is much more difficult to provide long lead times for ECCs than for ECAs.

5.5 SEARCH AREA AND LOCATION

The referent case described in Section 5.4 refers to a hypothetical whole-sky survey. Now we turn to realistic search strategies. What area of sky is it necessary to search, and in what locations, in order to discover a sample of ECAs and ECCs that is reasonably complete to an acceptable diameter threshold?

First we consider searching the maximum possible amount of dark sky. It is practicable to observe a region extending as much as ± 120 deg celestial longitude from opposition and ± 90 deg celestial latitude. In simulating such a survey, we include all the detection losses previously mentioned. Table 5-1 shows the calculated discovery completeness for a 25-year monthly dark-sky survey for ECAs. For $V = 22$ and all ECAs larger than 1-km diameter (potentially hazardous ECAs will be treated in more detail in Section 5.7.3), the discovery completeness would be very high: 95 percent. For $V = 24$, we would virtually achieve total completeness.

Table 5-2 shows the result of a perpetual monthly dark-sky survey for ECCs. Now, for $V = 22$ and $D > 1$ km, the completeness with a short warning time of three months is 77 percent. For $V = 24$, we would

Table 5-1. Dark-sky survey simulations for ECAs (see text for details). The table gives percentage discovery completeness for both entire population and potentially hazardous ECAs larger than a given diameter.

D	V = 22		V = 24	
50 m	3	5	16	25
0.1 km	12	19	42	55
0.5 km	76	84	97	98
1.0 km	95	96	99	99

Table 5-2. Dark-sky survey simulations for ECCs (see text). The percentages for zero warning time correspond to the overall discovery completenesses.

D > (km)	Warning time (yr)	% ECCs discovered	
		V = 22	V = 24
0.5	0.0	67	88
	0.25	54	83
	0.5	26	66
	1.0	5	16
1.0	0.0	85	94
	0.25	77	92
	0.5	59	84
	1.0	12	49
5.0	0.0	95	96
	0.25	93	95
	0.5	87	90
	1.0	68	79
	2.0	7	25
10.0	0.0	96	97
	0.5	90	93
	1.0	74	88
	2.0	18	74
	3.0	6	27

achieve 92 percent discovery completeness. In contrast to ECAs there is appreciable degradation of discovery completeness for ECCs arising from lack of observation at small solar elongations and low galactic latitudes.

Figure 5-3 indicates that a search centered on opposition (opposite the direction toward the Sun) is optimum. Surveys have been simulated that cover various areas of the sky and in which realistic detection losses have been included. In particular, simulations of 25-year surveys to magnitude limit $V = 22$ and for ECAs larger than 0.5-km diameter show that to minimize the area coverage needed to achieve a given discovery completeness, it is clearly advantageous to search regions spanning a broader range of celestial latitude than celestial longitude. The same strategy holds for other magnitude and diameter thresholds. For plausible search areas (in the range

5,000 to 10,000 square degrees per month), one may anticipate about two-thirds discovery completeness at $V = 22$. However, coverage in both longitude and latitude must not be too small or some ECAs will pass through the search region undetected from one month to the next.

Atens pose a special problem because some of them make very infrequent appearances that may occur far from opposition in celestial longitude. It can be expected that only about 40 percent of the Atens would be discovered in a nominal 25-year, 6,000-square-degree-per-month survey. The discovery rate could be increased to nearly 60 percent by biasing the search away from opposition, but at a sacrifice in the overall ECA discovery rate. It should be recalled that only eleven Atens are known, so the bias-corrected estimate of their true number may be substantially in error.

5.6 DISCOVERY COMPLETENESS

In what follows, it will be useful to consider a so-called standard survey region of 6,000 square degrees, centered on opposition and extending ± 30 deg in celestial longitude and ± 60 deg in celestial latitude.

5.6.1 Asteroids

To increase discovery completeness for a given search area and minimum ECA diameter, either the survey must be lengthened, the sky must be searched more frequently, the limiting magnitude must be increased, or detection losses must be reduced.

As noted above, rapid decline in the discovery rate of ECAs at faint magnitudes makes increasing the duration of the survey an ineffective strategy. For reference, the whole-sky survey to $V = 22$ and for diameters greater than 0.5 km could yield 71 percent completeness after 10 years. Even after 20 years, completeness would rise only to 81 percent (Fig. 5-4).

Scanning a given region of the sky twice a month is likewise not very effective. For the standard 6,000-square-degree survey region, to $V = 22$ and 0.5-km diameter threshold, the completeness after 25 years would rise from 66 percent to 69 percent. Scanning 12,000 square degrees once per month could lead to 72 percent completeness.

Figures 5-4 and 5-5 attest to the high value of mounting very deep surveys (that is, to very faint magnitude limits) for ECAs, the key factor being the greatly increased volume of space in which ECAs of given diameter can be detected. Figure 5-5 shows discovery completeness as functions of limiting magnitude V and diameter threshold for the standard survey region. At $V = 20$ and for diameter greater than 0.5 km, one can expect the standard 25-year

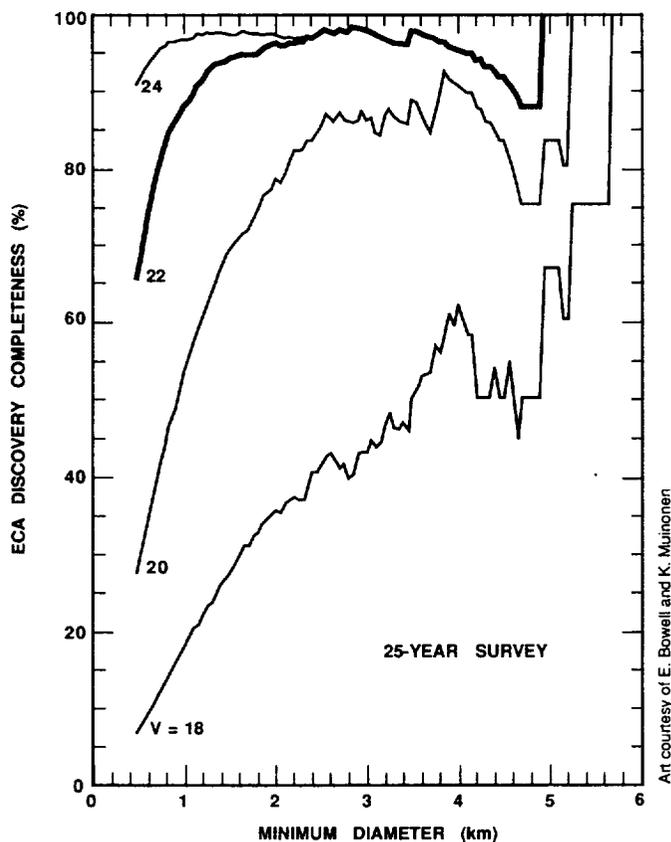


Figure 5-5. ECA discovery completeness as functions of threshold diameters and limiting magnitude V for the standard survey region (see text). In the bias-corrected model population examined, several large ECAs went undetected throughout the survey, even at faint V .

survey to be only 27 percent complete, whereas at $V = 22$ completeness rises to 66 percent. If the diameter threshold is 1 km, completeness should increase to 54 percent and 88 percent, respectively. Table 5-3 summarizes the results from the standard 25-year survey for ECAs, and shows that a significant fraction of small ECAs could be discovered.

Examination of the orbits of ECAs not discovered during simulated surveys shows, not unexpectedly, that most of these bodies' orbits have large semimajor axes, high eccentricities, and/or high inclinations such that either their dwell times in near-Earth space are brief and infrequent or they never come close to Earth in their present orbits. Of course, the latter class of ECAs poses no current hazard. This result of the simulations thus confirms our intuition: the survey preferentially discovers objects that come close to the Earth and therefore favors the overall objective of detecting the most hazardous asteroids.

5.6.2 Comets

No survey can aspire to completeness in the discovery of ECCs, since new comets are constantly

Table 5-3. Standard survey simulations for ECAs (see text). The table gives percentage discovery completeness for both the entire population and potentially hazardous ECAs larger than a given diameter.

D	V = 22		V = 24	
50 m	2	4	13	20
0.1 km	9	15	34	44
0.5 km	66	74	91	93
1.0 km	87	91	96	96

Table 5-4. Perpetual standard survey simulations for ECCs (see text). The percentages for zero warning time correspond to the overall discovery completenesses.

D >	Warning time	% ECCs discovered	
(km)	(yr)	V = 22	V = 24
0.5	0.0	23	42
	0.25	21	40
	0.5	9	28
	1.0	1	5
1.0	0.0	37	51
	0.25	35	49
	0.5	23	39
	1.0	3	15
	2.0	3	13
5.0	0.0	54	59
	0.25	53	58
	0.5	44	51
	1.0	22	34
	2.0	3	13
10.0	0.0	57	67
	0.5	49	62
	1.0	29	54
	2.0	8	40
	3.0	4	20

entering the inner solar system. Results for ECCs in a 6,000-square-degree per month survey to $V = 22$ and 24 are given in Table 5-4. As before, calculations are for a perpetual survey.

The warning time used in these calculations is actually the time from discovery to first Earth crossing. But it is equally likely that the ECC, if it is on a collision course, will strike Earth on the outbound part of its orbit, increasing the warning by a few weeks.

The overall level of completeness, without regard to warning time, is 37 percent at 1 km, 54 percent at 5 km, and 57 percent at 10 km diameter. Clearly, a survey designed for ECAs produces inferior results for ECCs, although the rate of discovery of these comets will be much greater than that achieved by current surveys, which rely upon relatively small telescopes and visual sky-sweeping by amateur as-

tronomers and miss the great majority of the smaller long-period comets.

5.7 SIMULATED SURVEY SCENARIOS

The simulations described above can be used to infer the nature of the observing activity during each monthly run of a major survey. The standard survey region of 6,000 square degrees per month can be studied for this purpose.

5.7.1 Discovery of Very Small ECAs

We have thus far not commented on very small ECAs discovered, although it is obvious that many tiny bodies, some just a few meters across, will be detected (see Tables 5-1 and 5-3). To estimate how many, 25-year surveys of the 320,000-member model population of ECAs larger than 0.1 km were simulated. From Fig. 5-6, which shows size-frequency distributions of ECA discoveries for various magnitude limits V , it may be seen that many more ECAs smaller than the nominal 1-km diameter threshold would be discovered. For a survey to $V = 22$, one would expect about 80,000 ECA discoveries, of which 60

percent are smaller than 0.1 km, 92 percent are smaller than 0.5 km, and 98 percent are smaller than 1 km diameter. In other words, for every object greater than 1 km diameter discovered in the standard survey, 50 more will be found that are smaller than 1 km.

5.7.2 Monthly Discovery Rate

What would be the discovery rate per month, assuming that the standard survey region of 6,000 square degrees were scanned? Figure 5-7 indicates that, to $V = 22$, one can expect more than 500 ECA discoveries of all diameters during the first month. This high initial monthly discovery rate is expected to tail off by a factor of about two over the course of a 25-year survey. The larger ECAs are preferentially discovered early, so that while about 5 percent of the ECAs discovered will be larger than 1 km diameter at the beginning of the survey, only 0.1 percent of the discoveries will be larger than 1 km diameter after 25 years. We estimate that ECCs larger than 0.5 km diameter will be discovered at a steady rate of about 15 per month.

5.7.3 Potentially Hazardous NEOs

Not all NEOs pose a threat to Earth. Many of them are in orbits that cannot, at present, bring them within a distance that we should be concerned about. The potential threat of an ECA or ECC can be gauged from the minimum distance of its orbit from that of the Earth (it can be assumed that, at some time or another, most ECAs will be located near the minimum distance). For ECAs that are not predicted to make very close planetary encounters (and thus will not have their orbits changed abruptly), we estimate that, over a timespan of a few hundred years, minimum Earth-encounter distances will not change by more than ten lunar distances (0.02-0.03 AU) in response to planetary perturbations. Thus, we can be sure that ECAs whose minimum inner-planet encounter distances are larger than, say, 0.05 AU (20 lunar distances), will not pose a threat to Earth in the coming centuries. Objects with smaller encounter distances we regard as potentially hazardous.

Because ECAs are preferentially observable when close to Earth, the completeness level for potentially hazardous ECAs is greater than that of the population as a whole. For a simulated 25-year dark-sky survey (Table 5-1), the discovery completeness for potentially hazardous ECAs larger than 1-km diameter is 96 percent, whereas it is 95 percent for the entire ECA population. For the standard 25-year survey (Table 5-3), the corresponding completenesses are 91 and 87 percent. For ECCs, however, the discovery completeness is the same as that of the total population (Tables 5-2 and 5-4).

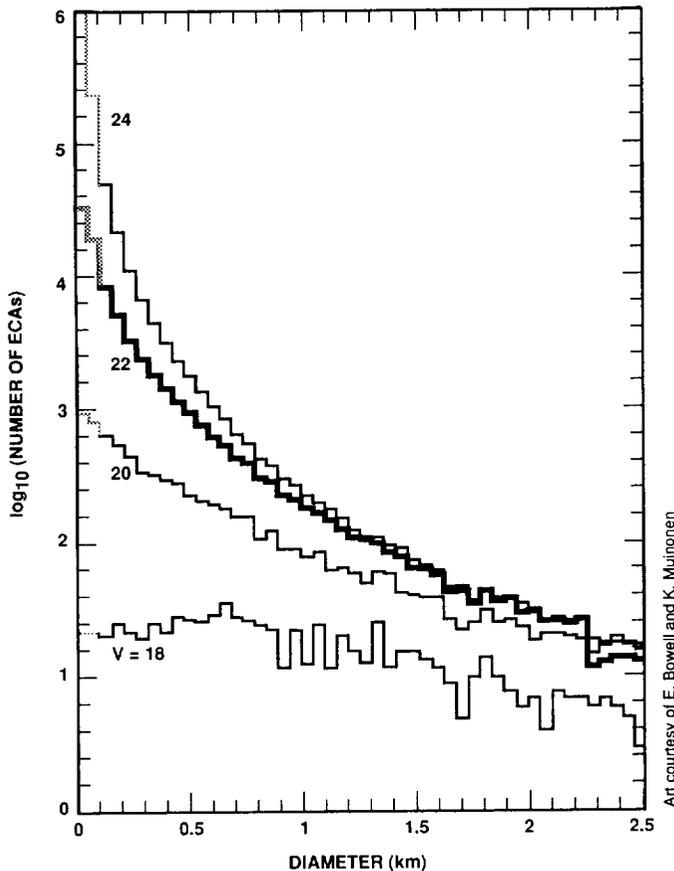


Figure 5-6. Size-frequency distribution of ECA discoveries for five magnitude limits resulting from simulated 25-year surveys (see text). The dotted lines are extrapolations from numerical simulations.

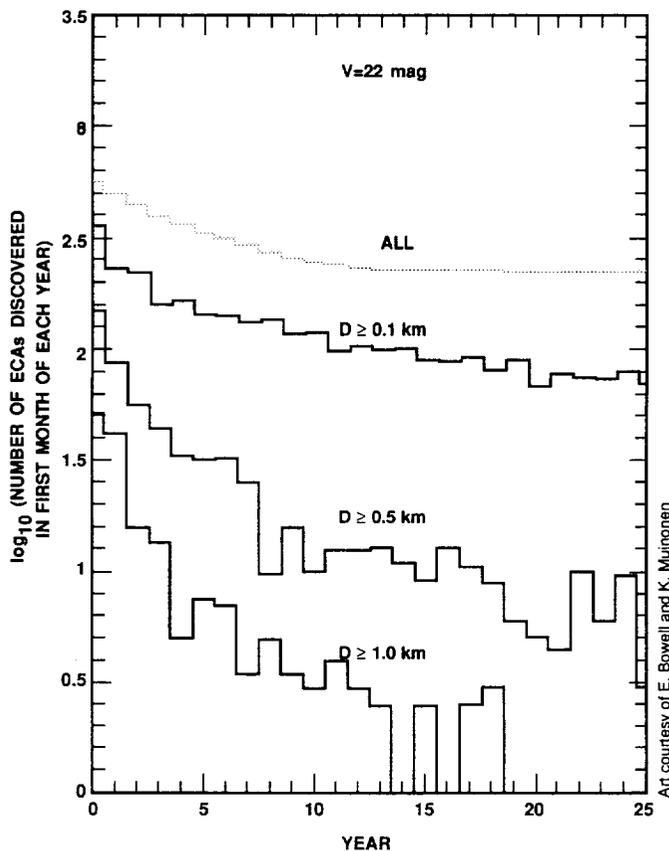


Figure 5-7. *Logarithm of the number of ECAs discovered in the first dark run of each year of a 25-year simulated survey (see text). Four histograms (upper to lower) are shown for all discoveries (dashed) and for diameter thresholds of 0.1, 0.5, and 1 km. The dashed histogram, for ECAs of all diameters, is extrapolated.*

As in Chapter 3, we note that 75 percent of the NEO hazard arises from ECAs and 25 percent from ECCs. If we specify a three-month warning time for ECCs, the percentages of potentially hazardous NEOs discovered during a 25-year dark-sky survey to limiting magnitude $V = 22$ are as follows: 76 percent for diameters greater than 0.5 km, 90 percent for diameters greater than 1 km, and 98 percent for diameters larger than 5 km. The corresponding percentages for a standard 25-year survey are: 61 percent for NEOs greater than 0.5 km diameter, 77 percent for NEOs greater than 1 km diameter, and 88 percent for NEOs greater than 5 km. At the larger sizes, the missed NEOs are almost all comets.

5.8 PRACTICAL CONSIDERATIONS IN SEARCH STRATEGY

It is inconceivable that a fully fledged network of completely equipped observing stations will start operation simultaneously and at full efficiency. More likely, current photographic and CCD searches will be intensified in parallel with the development of new survey telescopes. There exists, therefore, an important opportunity to refine models of the NEO population and to test observing strategies. In particular, care should be taken to preserve the pointing histories of any systematic searches for NEOs so more reliable bias correction can be carried out as the known sample grows. When a full-up survey is in progress, it will be possible to refine the population model further. For example, if it is determined that Atens are more numerous than currently thought, an improved survey strategy could be designed to enhance their discovery. Additional physical observations of newly discovered ECAs will also permit us to improve the model and thus develop better observing strategies.

We have shown that potentially hazardous ECAs can be discovered at a sufficient rate that most of the larger members of the ECA population can be discovered and assessed within 25 years. By prolonging the survey, the inventory of smaller ECAs can be brought to greater completeness. Indeed, we estimate that, using current technology to continue the standard survey beyond 25 years, we would stand a better-than-even chance, within a few hundred years, of discovering and identifying the ECA that might cause the next Tunguska-like event. In anticipation that huge strides in technological development would reduce this interval considerably, we can be almost certain that such an impactor could be identified by means of a prolonged telescopic search.

Since ECCs enter the inner solar system at a near-constant rate, many of them for the first time, their potential for hazard to Earth goes on forever. Thus, any survey of finite duration will be destined to ignore about 25 percent of the potential hazard posed to our planet. Only by continually monitoring the flux of ECCs in the Earth's neighborhood can we hope to achieve near-complete assessment of the NEO hazard.

CHAPTER 6

FOLLOW-UP OBSERVATIONS

6.1 INTRODUCTION

In the previous chapter we described a search strategy for the discovery of NEOs. However, additional follow-up observations are required. The uncertainty in the determination of the NEO orbit, and hence our ability to predict the object's future position, generally increases away from the period spanned by the observational data. If the positional data obtained during the discovery apparition are inadequate, then the uncertainty in the NEO's sky position during the next predicted apparition may be so large that the NEO cannot be recovered. The problem can be alleviated if the object is found in the existing file of observations of unidentified asteroids, but the object must otherwise be designated as lost, and it will remain lost until it is accidentally rediscovered. Clearly, we need to acquire sufficient data to minimize such loss of newly discovered objects.

An important part of the proposed survey involves the precise definition of NEO orbits, for this is a prerequisite to the identification of potentially hazardous objects. The critical first step in this process is to follow up each NEO discovery astrometrically; i.e., by tracking the object optically and/or with radar. Every NEO discovered should be followed astrometrically at least until recovery at the next apparition is assured. Further, we must develop explicit criteria for possibly hazardous ECAs, and any object that appears to fall into the "possibly hazardous" category on the basis of initial observations must be carefully tracked until an improved orbit determination allows a rigorous judgment as to its hazard potential.

In the case of an ECC, which cannot be tracked over several orbital periods, some uncertainty as to where (or even whether) it will strike the Earth may remain almost up to the time of impact. Smaller (Tunguska-class) ECAs may also require extensive tracking to determine their point of impact with sufficient accuracy (say 25 km) to permit rational judgments concerning countermeasures, such as the need to evacuate areas near the target. Finally, some uncertainty in the impact point will always remain due to lack of predictability of aerodynamic forces on the object in the Earth's atmosphere, especially if it breaks up during entry.

Apart from the astrometric follow-up observations, additional physical observations should be made to estimate the size and gross characteristics of the NEO. The rest of this chapter discusses various aspects of the follow-up process in detail.

6.2 RECOGNITION AND CONFIRMATION

Immediately after the discovery and verification of an NEO, the principal need is to secure enough astrometric data (observations of position and velocity) that the orbit can be determined with some reasonable reliability. Modern asteroid-hunting practice is to measure carefully the positions of the objects in relation to the stars, and to do so on two nights in quick succession. Although the above procedure is mainly designed for main-belt asteroids, its general features apply equally well to NEOs. The principal difference is that, because of its rapid motion, an NEO can generally be recognized as such on the night of its discovery, permitting the discoverer to plan for additional observations. In the case of an object moderately close to the Earth, the difference in perspective (parallax) arising from viewing points that are rotated about the center of the Earth (for example, at the same observatory but at times several hours apart) permits a rather accurate triangulation on the object's distance and hence contributes to the rapid determination of its orbit. In order not to interrupt the actual search process, it may be better to secure the additional initial-night observations with a different instrument or at a different site, although it is generally appropriate for the discoverer to take the responsibility for seeing that these observations are secured.

If an NEO is very close to the Earth, it is possible that enough information to compute a meaningful orbit can be obtained on a single night. Asteroid 1991 BA, which was observed eight times over only a five-hour interval, is an excellent example of this. If an initially computed orbit bears a resemblance to that of the Earth, however, it is quite probable that the object is an artificial satellite. There do exist artificial satellites in highly eccentric orbits with apogees at and even beyond the orbit of the Moon. In the recent case of tiny NEO 1991 VG, the earthlike orbit was verified as more observations became available, thereby introducing the troublesome possibility that this was an uncataloged artificial object that had completely escaped from the Earth's gravity long ago but that was now returning to the Earth's vicinity. As the quantity of "space junk" increases, similar problems are likely to occur.

The majority of the ECAs discovered will be visible only for relatively short time intervals because, being small, they must be close to Earth to be detectable. Indeed, the simulations discussed in Chapter 5 show that in a 25-year survey covering the standard

6,000-square-degree region to $V = 22$, the distance of closest approach of ECAs larger than 0.5 km diameter peaks at only about 50 lunar distances. The number of monthly observing runs during which ECAs larger than 0.5 km diameter can be detected in the standard survey region is shown as a function of limiting V in Fig. 6-1. At $V = 18, 20, 22,$ and 24 , the percentages of ECAs detected in only one run are 59, 41, 20, and 4 percent, respectively. The median numbers of monthly runs in which ECAs are detectable are 1, 2, 4, and 9, respectively, although a few are reobservable almost 30 times. At a diameter threshold of 1 km and for faint magnitudes, the percentages of ECAs observed in only one run are a factor of two smaller, and the median numbers of runs are increased by about 50 percent.

In the strategy described in Chapter 5, we did not directly address the use of the survey telescopes to obtain follow-up astrometric positions near the time of discovery. If follow-up observations were made out to, say, 60 deg longitude from opposition, the percent-

age of ECAs larger than 0.5 km seen only once to $V = 22$ would be reduced from 20 to 12 percent. Even greater protection against loss would be afforded by a follow-up strategy in which ECAs discovered were reobserved as long as possible in any accessible region of the dark sky. The question of strategy for this follow-up work needs further study, with the results depending on the availability of other supporting telescopes for astrometric observations.

Since losses after observation in one monthly run can be reduced to small numbers, it is probable that, for deep ECA surveys, follow-up can largely be ignored in favor of the linkage of detections from one run or one apparition to another. In general, such linkage can be achieved unambiguously provided observations are not too sparse. However, care must be taken not to lose the very fast-moving ECAs that may be most hazardous to Earth. Also, because of the large numbers of small ECAs that will be discovered, selection must be made, at least in part, on the basis of the diameter threshold. Both considerations call for a rapid estimate of the diameters of all ECAs discovered near the magnitude limit. To achieve this, the observed brightness can be combined with the distance gauged by means of diurnal parallax. Preference in such work should be given to those objects that appear to be true ECAs, especially those that might pose some threat based on initial orbit calculation.

6.3 OPTICAL ASTROMETRY

For a typical bright NEO, astrometric follow-up is essential. Much of the follow-up astrometry is most conveniently and efficiently accomplished using conventional reflecting telescopes fitted with CCDs. If conventional reflectors are used, they should generally be in the 1- to 2-m aperture range, although larger telescopes should certainly be considered for following up very faint discoveries. A set of semi-dedicated observatories is preferable to a single dedicated observatory (or one in each hemisphere), if only for reasons of weather and availability of observers, and there are certainly times when the more-or-less continuous coverage that may thereby be possible can be very useful.

Existing facilities currently involved with astrometric follow-up of NEOs are listed below in order westward from the principal U.S. discovery sites (the 0.46-m Schmidt at Palomar and the Spacewatch 0.9-m reflector at Kitt Peak), separately for each hemisphere:

Northern hemisphere:

- Victoria, B.C., Canada (0.5-m reflector with CCD);
- Mauna Kea, Hawaii (2.2-m U. Hawaii reflector and 3-m NASA IRTF with encoders);

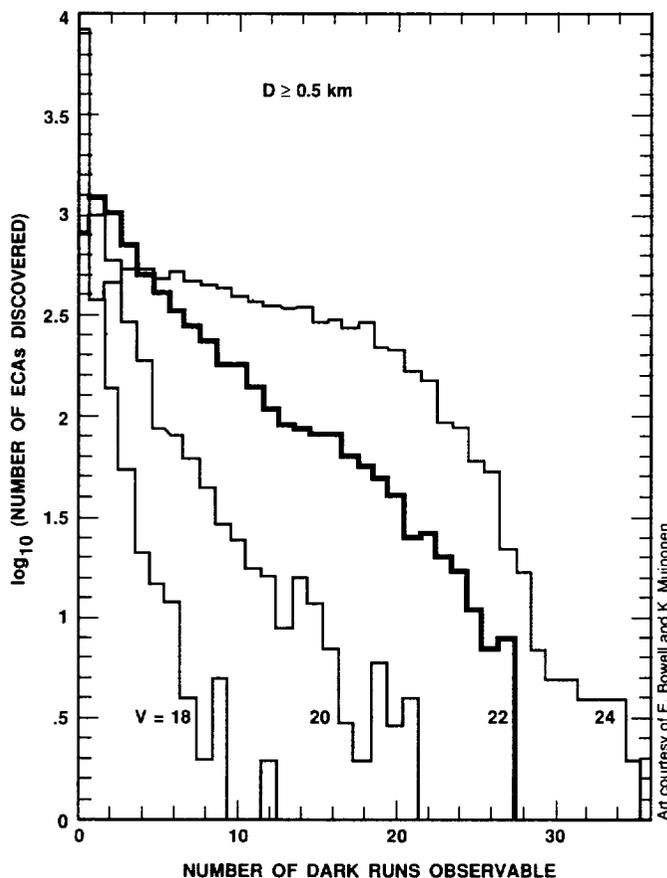


Figure 6-1. Logarithm of the number of ECAs larger than 0.5 km diameter discovered during a 25-year survey of the standard region (see text) as a function of the number of dark runs during which they are observable. Results for limiting magnitudes $V = 18, 20, 22,$ and 24 are shown. The leftmost bin, for zero dark runs, indicates the number of undiscovered ECAs: $\log n = 3.93$ ($V = 18$ mag), 3.82 (20), 3.50 (22), and 2.91 (24).

- Japan (no professional but much amateur activity);
- Kavalur, India (fledgling Spacewatch program);
- Kitab, Uzbekistan, and Crimean Astrophysical Observatory, Ukraine (0.4-m astrographs; coordinated by the Institute for Theoretical Astronomy, St. Petersburg, Russia);
- Kleť, Czechoslovakia (0.6-m Maksutov; currently no electronic-mail communication but should become possible via Prague);
- Western Europe (not much professional activity, but possibilities at Caussols, France, 0.9-m Schmidt, and La Palma, Canaries, 2.2-m reflector with CCD);
- Oak Ridge, Massachusetts (1.5-m reflector with CCD);
- Lowell Observatory, Arizona (1.1-m and 1.8-m reflectors with CCD).

Other possibilities include the 1.3-m Schmidt at Tautenburg, Germany, and telescopes at the Bulgarian National Observatory, but these are not currently involved with NEOs, and rapid communication is a problem.

Southern hemisphere:

- Mount John Observatory, New Zealand (0.6-m reflector, conversion to CCD in progress);
- Siding Spring, N.S.W., Australia (U.K. 1.2-m Schmidt, 0.5-m Uppsala Southern Schmidt, 1.0-m reflector with CCD);
- Perth, Western Australia, (occasional use of 0.3-m astrograph or 0.6-m reflector);
- European Southern Observatory, Chile (occasional use of 1.0-m Schmidt, 0.4-m astrograph or 1.5-m reflector).

Also, there would seem to be a need for participation in southern Africa and eastern South America.

6.4 RADAR ASTROMETRY

Radar is an essential astrometric tool, yielding both a direct range to an NEO and the radial velocity (with respect to the observer) from the Doppler-shifted echo (Yeomans and others 1987; Ostro and others 1991). Since most NEOs are discovered as a result of their rapid motion on the sky, these objects are then generally close to the Earth; radar observations are therefore often immediately possible and appropriate. However, radar observations do not become feasible until the object's expected position can be refined (from optical astrometry) to better than

about 1 arcmin, and an accuracy of 10 arcsec or better is preferable. A single radar detection yields astrometry with a fractional precision that is several hundred times better than that of optical astrometry, so the inclusion of radar data with the optical data in the orbit solution can quickly and dramatically reduce the future ephemeris uncertainty.

The principal radar instruments are currently those at Arecibo, Puerto Rico, and Goldstone, California. There may also be possibilities at Effelsberg, Germany; Parkes, N.S.W., Australia; and Yevpatoriya, Ukraine. Since radars are range limited, radar-detectability windows are narrow, but both Arecibo and Goldstone are being upgraded to enlarge their current windows. There is a clear need for a comparable facility in the southern hemisphere, and some preliminary planning has been done for an "Arecibo-class" radio telescope in Brazil which could also be used as a radar.

The inclusion of radar data in the orbital solutions would allow an NEO's motion to be accurately integrated forward for many decades to assess the likelihood of future Earth impacts. With optical data alone, such an assessment requires an observational span of several decades, which may or may not be possible from the inspection of old photographic plates. The addition of radar data to the orbital solution may allow reliable extrapolations of the object's motion to be made within only days of discovery.

There has hitherto always been a time interval, at least several days long, between discovery and the initial radar work. If the first radar ephemeris is found to have very large delay or Doppler errors, the initial radar astrometry is used to generate a second-generation radar ephemeris to enable finer-precision delay or Doppler astrometry (by at least a factor of ten) than would have been possible with the first radar ephemeris. This bootstrapping process would be much more efficient than it currently is if a capability to do the computations existed at the radio telescope itself. Ideally, one could input the first measurements of Doppler and delay into a program on a computer at the site, generate an improved ephemeris within an hour of initial detection, and proceed immediately to high-resolution ranging. The existence of on-site ephemeris-generating capability would be essential if the astrometry that does the critical shrinking of the pointing uncertainty becomes available at the same time as the object enters the radar window, or with an NEO that comes so close that it traverses the telescope's declination-distance window in one day (as did comet IRAS-Araki-Alcock at Arecibo in 1983).

6.5 PHYSICAL OBSERVATIONS

The impact energy of an NEO that actually hits the Earth depends on both its velocity and its mass. Knowledge of the orbit provides only the velocity, not the mass. The latter quantity can be estimated only from physical observations. If astrometric observations are made with a photometric device, such as a CCD, they can also provide information about the most basic of physical parameters, namely, the brightness of the object. In the case of a bright comet, measurements of the brightness will almost certainly include a strong contribution from the comet's atmosphere, whereas what is needed is isolation of the solid nucleus, something that can be satisfactorily attempted only when the comet is farther from the Sun.

Although an asteroid's brightness is correlated with its size, the known range of asteroid surface reflectivities spans a factor of 20, which leads to a large uncertainty in the volume. The range of densities of asteroids can be inferred from their bulk compositions, which may in turn be suggested by measurements of surface composition. If only a brightness measurement is available, the deduced mass of the object, and therefore the potential impact energy, can be uncertain by a factor of a hundred. Additional uncertainty arises from the fact that asteroid brightnesses vary as they rotate, sometimes by more than a factor of five.

Measurements of the relative reflectivity of an asteroid at a variety of wavelengths (its spectral reflectivity) can place the object in one of several known taxonomic classes and therefore reduce the uncertainty in the surface reflectivity. At the same time, the composition of the object is constrained, leading to an improved estimate of the bulk density. In a minimal effort, the use of three filters, appropriately chosen to sample spectral features in the ultraviolet and infrared regions, should be employed. With additional filters, greater diagnosticity can be achieved, with a corresponding improvement in reflectivity and composition estimates. With a minimal filter set, the uncertainty in the range of potential impact energies can be reduced to a factor of about ten.

Radar observations are the only source of spatially-resolved measurements from the ground and hence provide the only source of direct information about an NEO's shape. Moreover, radar can also supply constraints on size that are highly reliable if the echoes are strong enough. Radar also provides some information about the composition and roughness of an NEO's surface.

Even single-color photometry permits a rotation period to be determined, and radar can then provide the spin-pole direction. The angular momentum of a potentially hazardous object can therefore be calculated, and this may be an important consideration in deciding on the technique to be used for dealing with the hazard. In the case of a comet, the detection of persistent cyclic variations in the brightness of the condensation about a stable mean is probably an indication that the solid nucleus has been detected.

That NEOs differ greatly in composition is also evident from a comparison of the effects of encounters. Although the bodies that produced Meteor Crater in Arizona 50,000 years ago and the Tunguska event in Siberia 84 years ago are both thought to have been in the rough size range 50 to 100 m, one produced a crater that is still well-preserved, while the other apparently exploded high above the ground, produced no crater, but levelled trees over a much larger area. Knowledge of the likely composition can also play a prominent role in establishing the ameliorative action that might be taken in the case of a predicted impact.

One could argue that it is not necessary to make physical observations until an object on a collision trajectory has actually been detected. This may not be a prudent course of action, however, for the following reasons. (1) The possibility exists that there will be no further opportunity to study the object in question sufficiently in advance of a collision to provide the necessary information on the potential impact energy and on how to deal with the object. (2) Discoveries of NEOs are often made when they are unusually close to the Earth, and physical observations can be performed more efficiently and with higher precision at these times. (3) We need to learn more about the full range of NEO compositions and structural properties, which are poorly known at present, in order to plan possible strategies for deflection of these objects in case of a predicted impact. (4) There are significant scientific and possible future space exploration benefits that can result from the study of a sizable portion of the NEO population, including the identification of objects with space resource potential (substantial sources of water or of nickel-iron and other heavy metals), the providing of selection criteria for possible future spacecraft missions to such objects, the understanding of the link between terrestrial meteorites and the asteroid belt, and important information regarding the origin (cometary versus asteroidal, for example) of these objects.

6.6 SURVEY CLEARINGHOUSE AND COORDINATION CENTER

Much of the discussion in this chapter has been in the context of current practice for NEO discoveries. However, the proposed new search strategy described in Chapter 5 means that future NEO discoveries may take place up to 5 magnitudes, or 100 times, fainter than at present. When searches routinely reach magnitude 22 there should be about 500 new NEO candidates each month. With careful organization of the discovery searches, however, the astrometric follow-up data could all be obtained with the same telescopes involved in the discovery. In particular, thought should be given to ensuring that the relevant fields are automatically recorded with a large time separation on either the first or the second night in order to make a parallactic determination of a crude orbit. Month-by-month opposition scanning should also allow, at least in principle, the correct identification of subsequent images of each NEO, but in order to ensure success it would probably be desirable to perform the discovery and confirmation regimen twice during each monthly run.

Bright time (that is, time when the Moon is up) on the discovery telescopes could also be used for physical observations. Radar observations would presumably have to be restricted to close passages by the Earth. Sampling of the physical properties of the smaller NEOs would be important in case they are systematically different from those of the larger NEOs and the main-belt asteroids. However, their faintness makes certain observations difficult, so that a large dedicated follow-up telescope with special instrumentation would prove more effective for some physical observations than would the survey telescopes themselves.

The dramatic increase in the rate of discovery of NEOs will require considerable extension of the current system for keeping track of these objects and disseminating information about them. Hitherto these functions have principally been carried out by the International Astronomical Union's Central Bureau for Astronomical Telegrams and Minor Planet Center, which since 1978 have been operating together at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, under the direction of B. G. Marsden. The Minor Planet Center currently deals with asteroid discoveries (primarily main-belt objects) at an annual rate of a few thousand. With the prospect of discovering a thousand NEOs alone in a month, augmentation of the Minor Planet Center's capabilities will be necessary.

Procedures for rapidly checking, identifying, computing orbits and providing appropriate ephemerides for new discoveries are already in place, but future enhancement will require acquisition of faster computers and the employment of additional personnel. The future NEO survey clearinghouse would also undertake the task of actually planning the observations at the various sites, collecting the observations from the sites, and coordinating further observations to cover fields missed by bad weather and to ensure proper follow-up in specific cases.

Further development of procedures and construction and maintenance of software must also be an important component of the work of the survey clearinghouse. For comets and asteroids, the computation of an orbit and ephemeris should include an estimate of the uncertainty in the NEO's location as a function of time, that is, the "positional error ellipsoid" (Yeomans and others 1987; Muinonen and Bowell 1992). (This is less easily done in the case of comets because of the existence of nongravitational effects that can at best be modeled in a semi-empirical manner.) By projecting the error ellipsoid into the future, one can quantify the likelihood that an NEO will be recoverable, and one can also assess the uncertainty in an Earth-asteroid distance for any future close approaches. Such software will also (1) help to expedite verification of newly discovered objects as NEOs, (2) provide the basis for prioritizing NEOs for follow-up astrometry, both to avoid losing objects and to optimize the use of telescope time and personnel, and (3) permit the reliable identification of NEOs on very close-approach trajectories and the appropriate hazard assessment.

For each newly discovered NEO, data files will have to be established to catalog discovery data and follow-up observations, both astrometric and physical. Orbits and associated error analyses will be required for each object to identify close Earth approaches in the immediate future and to establish optimum observation times for securing the object's orbit and ensuring its recovery at subsequent observation opportunities. Once the need for follow-up observations has been established and the optimal observation times determined, the clearinghouse would notify the appropriate people capable of making the required observations and provide them with all the information required to utilize efficiently the limited amount of available telescope time. Recently, a NASA center for some of these clearinghouse activities has been established at the Jet Propulsion Laboratory.

CHAPTER 7

PROPOSED SEARCH PROGRAM

7.1 INTRODUCTION

In this chapter, we assess the instrumental requirements (telescopes, mosaics of CCD chips, computers, etc.) imposed by the observing strategy and follow-up research outlined in Chapters 5 and 6, and we comment on observational techniques and observing network operation. We concentrate on the requirements of a survey optimized for the discovery of ECAs, with the understanding that slightly different requirements are posed by a network optimized for an ECC search. In order to cover the requisite volume of search space, the survey must achieve a stellar limiting magnitude limit of at least $V = 22$, dictating telescopes of 2- to 3-m aperture equipped with CCD detectors. The most efficient use of CCD detectors is achieved if the pixel size is matched to the apparent stellar image size of about 1 arcsec, thus defining the effective focal length for the telescopes at about 5 m. According to the model explored in Chapter 5, the area of sky to be searched is about 6,000 square degrees per month, centered on opposition, and extending to ± 30 deg in celestial longitude and ± 60 deg celestial latitude. These considerations lead us to a requirement for multiple telescopes with moderately wide fields of view (at least 2 deg) and mosaics of large-format CCD detectors. We develop these ideas in this chapter to derive a proposed search program. This program is not unique (that is, an equivalent result could be obtained with other appropriate choices of telescope optics, focal-plane detectors, survey area, and locations), but it is representative of the type of international network required to carry out our proposed survey.

7.2 LESSONS FROM THE SPACEWATCH PROGRAM

The Spacewatch Telescope, operated at the University of Arizona (see Chapters 3 and 4), is the first telescope and digital detector system devised to carry out a semi-automated search for NEOs. As such, the lessons learned from its development and operation are invaluable when considering a future generation of scanning instruments. The Spacewatch system comprises a single 2048x2048-pixel CCD chip at the $f/5$ Newtonian focus of an equatorially mounted 0.9-m telescope. Each pixel covers 1.2×1.2 arcsec on the sky. With the telescope drive turned off, the camera scans the sky at the sidereal rate, and achieves detection of celestial bodies to a limiting magnitude $V = 20.5$.

One of the important demonstrations provided by the Spacewatch Telescope team is that image-recognition algorithms such as their Moving Object Detection Program (MODP) are successful in making near-real-time discoveries of moving objects (asteroids and comets). False detections are almost eliminated by comparing images from three scans obtained one after the other. At present, the Spacewatch system makes detections by virtue of the signal present in individual pixels. With the incorporation of higher-speed computers, near-real-time comparison of individual pixels to measure actual image profiles would lead to a great reduction in the most frequent sources of noise, cosmic ray hits and spurious electrical noise events.

In light of the successful performance of Spacewatch, we have rejected a photographic survey. Even though sufficiently deep exposures and rapid areal coverage could be attained to fulfill the survey requirements using a small number of meter-class Schmidt telescopes (similar to the Oschin and U.K. Schmidts), there is no feasible way, either by visual inspection or digitization of the films, to identify and measure the images in step with the search. A photographic survey would fail for lack of adequate data reduction and follow-up. Future developments in electronics and data processing will further enhance the advantages of digital searches over the older analog methods using photography.

7.3 DETECTOR AND TELESCOPE SYSTEMS

The largest CCD chips readily available today contain 2048x2048 pixels, each about 25 micrometers on a side. Thus, the chips are about 5×5 cm in size. Quantum efficiencies have attained a peak near 80 percent, and useful sensitivity is achievable from the near-ultraviolet to the near-infrared. To reach a limiting stellar magnitude of $V = 22$, we require the use of these CCDs at the focal plane of a telescope with an aperture of 2 m or larger, operated during the half of the month when no bright moonlight is present in the sky (from last quarter to first quarter phase).

In the coming decade, we envisage a trend toward smaller and more numerous CCD pixels covering the same maximum chip area as at present. No great increase in spectral sensitivity can be expected. At the telescope, the pixel scale must be matched to the image scale (the apparent angular size of a stellar image) in good or adequate atmospheric (seeing) conditions. In what follows, we assume a pixel scale

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of 1 arcsec/pixel (25-micrometer/arcsec, or 40 arcsec/mm), which implies a telescope of 5.2-m focal length. For a telescope of 2 m aperture, the focal ratio is $f/2.6$; for a 2.5-m, $f/2.1$; and for a 3-m, $f/1.7$.

A single 2048x2048 CCD chip simultaneously detects the signals from more than 4 million individual pixels. This is a very powerful data-gathering device, but it still falls short of the requirements for wide-field scanning imposed by the proposed NEO survey. At the prime focus of a telescope of 5.2-m focal length, such a CCD covers a field of view on the sky about one-half deg on a side. However, we wish to scan an area at least 2 deg across. Therefore, we require that several CCD chips be mounted together (mosaicked) in the focal plane. The mosaicking of CCD chips is being vigorously pursued today by astronomers; at Princeton University, for example, a focal plane with 32 CCDs is under development.

Studies and planning are underway at the University of Arizona for a modern 1.8-m Spacewatch telescope. The new telescope will be an excellent instrument to test and develop some of the necessary instrumental and strategic considerations outlined in this report. From the Spacewatch design considerations, it is safe to assume that 2- to 3-m-class telescopes can be built having focal lengths near 5 m and usable fields of view between 2 and 3 deg. Refractive-optics field correction is probably required, and it appears advantageous to locate CCD mosaics at the prime focus of such instruments. Here, we indicate telescope functional requirements but do not exactly specify the size or design of the proposed survey telescopes.

7.4 MAGNITUDE LIMIT AND OBSERVING TIME

Exceptionally fine astronomical sites have more than 1,000 hr/yr of clear, moonless observing conditions, during most of which good to adequate seeing prevails. More typically, 700 hr/yr of observing time is usable. We assume that a region of 6,000 square degrees is to be searched each month and that initial NEO detection is made by two or three scans on the first night. Parallax information is derived by four scans on a subsequent night, and an orbit is calculated from observations on a third night. Thus, nine or more scans of the search region are needed each month. In a given month, follow-up will be attempted for some of the NEOs that have moved out of the search region (mainly to the west). As a working value, we assume that 40 hr/month per telescope are available for searching.

The limiting (faintest) stellar magnitude that can be observed by a telescope can be determined as a function of the ratio of the source brightness to that of

the sky, the number of pixels occupied by a star image, the pixel area, the light-collecting area of the telescope, and the effective integration time (Rabinowitz 1991). For certain detection, the source brightness must be at least six times that of the sky noise. We have normalized to the performance of the Spacewatch Telescope, which achieves a stellar limit of $V = 20.5$ using an unfiltered 165-sec scan at sidereal rate, and we have allowed for an improvement over the performance of that system arising from improved detector quantum efficiency and improved image-recognition algorithms. We find for the survey telescopes that a single CCD should be able to achieve the survey requirement of $V = 22$ with the following combinations of telescope aperture and scan speed:

Primary Diameter (m)	Exposure Time (s)	Scan Rate (x sidereal)
2.0	21	6
2.5	14	10
3.0	10	14

7.5 NUMBER OF CCD CHIPS AND TELESCOPES REQUIRED

A single 2048x2048-pixel CCD chip, having an image scale of 1 arcsec/pixel, can scan at 0.14 square degrees per minute at the sidereal rate. If 40 hr/month/telescope can be allotted to searching for NEOs over 6,000 square degrees to a limiting stellar magnitude of $V = 22$, and ten scans per sky region are required for detection and rough orbital characterization of an NEO, then telescopes of the apertures considered above have the following performance capabilities:

Primary Diameter (m)	Area/month/CCD (sq. deg)	Total number of CCDs required
2.0	260	28
2.5	420	18
3.0	600	13

In computing values for the total number of CCD chips required in the worldwide network of telescopes we assume that no two CCD chips together scan the same region of the sky. These are minimum requirements for the telescopes; in practice more scans may be needed for reliable automatic detection, and

probably there will be some overlap of coverage between telescopes.

Searching to ± 60 deg celestial latitude implies sky coverage, over the course of a year, at almost all declinations. Thus telescopes must be located in both hemispheres. Usable fields of view of between 2 and 3 deg probably limit the number of CCD chips in a telescope's focal plane to about ten at the scales we have been considering. However, real-time image processing is simplified if each chip independently samples the sky. Most likely, four CCD chips/telescope can be accommodated in a linear array in the focal plane. Thus, it appears that seven 2-m telescopes, five 2.5-m telescopes, or four 3-m telescopes suffice to fulfill the search, follow-up, and physical observations requirements of the idealized 6,000-square degree survey. Most likely, there would remain extra observational capability to enhance the detection rates of Atens and ECCs by scanning a few times per month outside the standard region. We note that each telescope must be equipped with a minimum of four 2048x2048 CCD chips or their equivalent in light-collecting ability. If space remains in the focal plane, additional filtered CCD chips could be inserted to undertake colorimetry, which would give a first-order compositional characterization of some of the NEOs discovered while scanning.

To ensure that a single-point failure due to weather or other adverse factors will not hamper effective operation of the survey network, we conclude that three telescopes are required in each hemisphere. With fewer telescopes, orbital, and perhaps parallactic, information on NEOs would be sacrificed. The desirability of searching near the celestial poles calls for at least one telescope at moderate latitude in each hemisphere. In summary, we propose a network of six 2-m or larger telescopes distributed in longitude and at various latitudes between, say, 20 deg and 40 deg north and south of the equator.

7.6 SCANNING REGIME

At high declinations, scanning along small circles of declination results in curvature in the plane of the CCD chip, so star images do not trail along a single row of pixels. The problem can be avoided by scanning along a great circle. A good strategy would be to scan in great circles of which the ecliptic is a meridian (the pole being located on the ecliptic 90 deg from the Sun). Such scanning can be achieved using either equatorial or altitude-azimuth telescope mounts, but is probably more easily and cheaply accomplished using an altitude-azimuth mount. In either case, field rotation is required, as is currently routinely used at the Multiple-Mirror Telescope in Arizona and other installations.

At the proposed 1.8-m Spacewatch telescope, it is planned to make three scans of each region of the sky (as is currently done at the 0.9-m Spacewatch telescope). Each scan would cover 10 deg in 26 min, so the interval between the first and third scans is sufficiently long that objects moving as slowly as 1 arcmin/day can be detected. For the proposed NEO survey, we envisage two or three longitudinal scans per sky region, about an hour apart. Thus, at a scan rate of 10 times sidereal, each scan could cover an entire strip of the 60-deg-wide search region, with a second search strip being interposed before the first was repeated. We assume that occasional false positive detections will not survive scrutiny on the second night of observation, and thus will not significantly corrupt the detection database.

7.7 COMPUTER AND COMMUNICATIONS REQUIREMENTS

Near real-time detection of faint NEOs requires that prodigious amounts of data processing be accomplished at the telescope. The image processing rate scales linearly with the number of objects (NEOs, stars, galaxies, noise, etc.) recorded per second. The number of objects detected per second (the "object rate"), and therefore computer requirements of the NEO survey outlined above, can be estimated from the current performance of the Spacewatch Telescope. The computer system in use at the Spacewatch Telescope can detect up to 10,000 objects in a 165-sec exposure. Thus, its object rate is 60/sec. Scanning to $V = 22$ requires detection of about 30,000 objects/square degree. For an image scale of 1 arcsec/pixel, using the scanning rates tabulated above, and allowing a ten-fold increase in computing requirements to perform real-time image profile analysis, we calculate the total network computer requirement to be 2,000 to 3,000 times that at the Spacewatch Telescope. Therefore at each of six telescopes, it would be 300 to 500 times that at Spacewatch. Such a requirement, although not easy to achieve, is possible using the newest generation of parallel processors.

There are at least three levels of observational data storage that can be envisaged: (1) preservation of image-parameter or pixel data only for the moving objects detected; (2) preservation of image-parameter or pixel data for all sources detected (mostly stars); (3) storage of all pixel data. The first option is clearly undesirable, because data for slow-moving NEOs mistaken as stars would be lost. The first two options have the disadvantage that there would be no way to search the database, after the event, for sources whose brightnesses are close to the limiting magnitude and that would therefore have been discarded. The third option—the most attractive scientifically—may

appear to result in serious problems of data storage and retrieval. However, we anticipate that, using technology shortly to be available, the third option is tractable.

About 500 NEOs and one hundred thousand main-belt asteroids could be detected each month—about one detection per second of observing time. Therefore, only moderate-speed data communication is needed between observing sites and a central-processing facility. Careful observational planning will be

required to ensure efficient coverage of pre-programmed scan patterns, to avoid unintentional duplication of observations, to schedule the necessary parallactic and follow-up observations, and to optimize program changes so as to maintain robustness of the survey in response to shutdowns. Successful operation of this survey system will also require the coordination and orbital computation capabilities of a modern central data clearinghouse as described in Chapter 6.

CHAPTER 8

INTERNATIONAL COOPERATION

8.1 THE NECESSITY OF INTERNATIONAL COOPERATION

That the hazard posed by NEOs is a problem for all humankind hardly needs repeating. The likelihood of a particular spot being the target of an impact is independent of its geographic position, so that we are all at risk. Further, each person on the face of the planet would be severely affected by a large impact, as discussed in Chapter 2.

The problem is thus international in scope; it is also international in solution. To obtain the spatial and temporal coverage of the sky that is required by the search program outlined in Chapter 7, a wide geographical coverage of optical observatory sites is essential. Even if these sites were limited to six, still at least five countries would likely be involved directly as telescope hosts. However, the number of nations actually involved would be larger than this. If Australia were one site then most likely the Anglo-Australian Observatory would be the organization acting as host, implying British involvement. Similarly a site in India, where a Spacewatch-type instrument is currently being developed, might involve a continuation of direct U.S. collaboration. Some of the best observatory sites in the southern hemisphere are in Chile, and if plans go ahead for the development of a large southern radar in Brazil, again the number of countries increases. The need for international cooperation is obvious, and rapid and efficient international communication through a central agency is a requirement.

8.2 CURRENT INTERNATIONAL EFFORTS

The independent character of the scientific endeavor as well as limited funding resources has resulted in a current program to find and track NEOs that is quite fragmentary. Generally it has been possible, in recent years, for discoveries made by one team to be followed up by other observers, but this has not always been the case, allowing some newly discovered NEOs to be lost. For the program planned here this must not be allowed to occur, emphasizing the need for an international effort with close cooperation and priorities to be set by a central organization. The present level of our knowledge of NEOs has been possible only because of the services of the staff of the Central Bureau for Astronomical Telegrams and the Minor Planet Center (Cambridge, Massachusetts) who coordinate the analysis of discoveries of NEOs and make every effort to ensure that sufficient

coverage occurs. A continuation of such a service on a much larger scale will be necessary if the proposed program is to be brought to fruition.

There have been efforts to formally organize a search program on an international scale, quite apart from the informal links and communications made possible by personal contacts. The most prominent of these organizations has been INAS, the International Near-Earth Asteroid Survey, coordinated by E. F. Helin (Helin and Dunbar, 1984, 1990). INAS has resulted in increased cooperation among observatories in various countries, and hence a modest increase in the discovery rates. Apart from the U.S., scientists from the following countries have been involved in INAS: Australia, Bulgaria, Canada, China, Czechoslovakia, Denmark, France, Germany, Italy, Japan, New Zealand, Russia, Sweden, Ukraine, United Kingdom, and Yugoslavia.

The major thrust of INAS has been to coordinate the efforts of the large wide-field photographic instruments with regard to temporal and sky coverage. An immediate expansion of this effort can increase the current discovery rate, thus providing valuable information on the true statistical nature of the NEO population and associated impact hazards before the full network of survey telescopes becomes operational. Such a program will also serve as a training ground for new personnel and provide valuable experience with improved international communication and coordination.

A Spacewatch-type telescope is currently under development in India with the joint support of the U.S. Smithsonian Institution and the Government of India. Another international effort is being proposed by the Institute for Theoretical Astronomy in St. Petersburg, Russia, under the direction of A.G. Sokolsky. This group organized an international conference, "The Asteroid Hazard," in October 1991, which endorsed the idea that NEOs "represent a potential hazard for all human civilization and create a real threat of regional catastrophes" and noted "the necessity of coordinated international efforts on the problem of the asteroid hazard." This group has asked the Russian Academy of Science to support the formation of an International Institute on the Problem of the Asteroid Hazard under the auspices of the International Center for Scientific Culture — World Laboratory, and they propose to coordinate asteroid searches and follow-up observations in central and eastern Europe.

8.3 FUNDING ARRANGEMENTS

If this international survey program is to succeed, it must be arranged on an inter-governmental level. To ensure stability of operations, the NEO survey program needs to be run by international agreement, with reliable funding committed for the full duration of the program by each nation involved.

There are good reasons for the funding to be derived from all nations directly involved in the program. First, most countries usually want to provide for their own defense rather than to rely upon another or others to do this for them, so we may anticipate that nations in the world-wide community will wish to each play their own part in defending the planet. Second, although this program is large compared with present NEO search efforts, in fact it would be of quite a small overall budget. Thus it is possible for nations to make a significant contribution with little expense whereas it would not be possible for them to buy into a large space project, or even the construction of a ground-based 10-m-class astronomical telescope. For example, there is a small group in Uruguay that studies dynamical aspects of NEO's, and they could provide an essential service to the program; or the telescopes available for follow-up work in New Zealand or Romania could be utilized, and thus those nations could gain prestige on the international scene at little expense. Involvement in space programs (which this program is, in essence) is generally viewed favorably by the populace of most countries. Third, this program may be a significant technology driver for small countries, so that money spent on the investigation and development of new technologies can be viewed as an investment rather than an expenditure.

With the encouragement of the United States as prime mover, the funding for national sectors of the overall international search program should be attainable locally. For example, Australia and the United Kingdom, through their joint observatory in Australia, could immediately boost the current discovery rate to about 100 per year using existing equipment and technology, given supplementary funding from those countries of the order of \$0.25 million per year, although we would anticipate that this effort would be superseded by the introduction of CCD detectors within five years. Photographic searches currently being carried out in the United States might require a similar boost in funds, with a concomitant boost in discovery rate resulting, and the Spacewatch effort could also be significantly expanded by approval for the upgrade to 1.8-m aperture and funding to run the camera on more than eighteen nights per month.

8.4 INTERNATIONAL SANCTION

The astronomical program outlined in this report already has the support of various international bodies. There is a burgeoning awareness in the astronomical community that the NEO impact hazard is a topic that requires attention for reasons other than altruistic scientific pursuit. At the 1991 General Assembly of the International Astronomical Union held August 1, in Buenos Aires, Argentina, the following resolution was passed:

The XXIst General Assembly of the International Astronomical Union,

Considering that various studies have shown that the Earth is subject to occasional impacts by minor bodies in the solar system, sometimes with catastrophic results, and

Noting that there is well-founded evidence that only a very small fraction of NEO's (natural Near-Earth Objects: minor planets, comets and fragments thereof) has actually been discovered and have well-determined orbits,

Affirms the importance of expanding and sustaining scientific programmes for the discovery, continued surveillance and in-depth physical and theoretical study of potentially hazardous objects, and

Resolves to establish an ad hoc Joint Working Group on NEOs, with the participation of Commissions 4, 7, 9, 15, 16, 20, 21 and 22, to:

- 1. Assess and quantify the potential threat, in close interaction with other specialists in these fields,*
- 2. Stimulate the pooling of all appropriate resources in support of relevant national and international programmes,*
- 3. Act as an international focal point and contribute to the scientific evaluation, and*
- 4. Report back to the XXIIInd General Assembly of the IAU in 1994 for possible further action.*

The Working Group, to be convened by A. Carusi of Italy, comprises the following scientists:

- A. Basilevsky (Russia)
- A. Carusi (Italy)
- B. Gustafson (Sweden)
- A. Harris (USA)
- Y. Kozai (Japan)
- G. Lelièvre (France)
- A. Levasseur-Regourd (France)
- B. Marsden (USA)
- D. Morrison (USA)
- A. Milani (Italy)
- K. Seidelman (USA)

- E. Shoemaker (USA)
- A. Sokolsky (Russia)
- D. Steel (Australia/UK)
- J. Stohl (Czechoslovakia)
- Tong Fu (China)

This Working Group was selected not only on the basis of the geographical spread of persons active in the general area, but also in terms of expertise in distinct areas of the necessary program (e.g., celestial mechanics, generation of ephemerides, physical nature of NEOs, dynamics of same, relationship to smaller meteoroids and interplanetary dust). Five of these 16 individuals are also members of the NASA International NEO Detection workshop, ensuring appropriate continuity of effort.

CHAPTER 9

THE SPACEGUARD SURVEY: SUMMARY

9.1 OVERVIEW

Concern over the cosmic impact hazard motivated the U.S. Congress to request that NASA conduct a workshop to study ways to achieve a substantial acceleration in the discovery rate for near-Earth asteroids. This report outlines an international survey network of ground-based telescopes that could increase the monthly discovery rate of such asteroids from a few to as many as a thousand. Such a program would reduce the time-scale required for a nearly complete census of large Earth-crossing asteroids (ECAs) from several centuries (at the current discovery rate) to about 25 years. We call this proposed survey program the Spaceguard Survey (borrowing the name from the similar project suggested by science-fiction author Arthur C. Clarke nearly 20 years ago in his novel *Rendezvous with Rama*).

In addition, this workshop has considered the impact hazards associated with comets (short-, intermediate-, and long-period) and with small asteroidal or cometary objects in the size range from tens of meters to hundreds of meters. The object is not elimination of risk, which is impossible for natural hazards such as impacts, but reduction of risk. Emphasis, therefore, is placed upon the greater hazards, in an effort to define a cost-effective risk-reduction program. Below we summarize our conclusions with respect to these three groups of objects: large ECAs, comets, and small (Tunguska-class) objects.

1) **Large ECAs** (*diameter greater than 1 km; impact energy greater than 100,000 megatons*). These objects constitute the greatest hazard, with their potential for global environmental damage and mass mortality. About two thousand such objects are believed to exist in near-Earth space, of which fewer than 10 percent are now known. About a quarter of them will eventually impact the Earth, but the average interval between such impacts is long — about 100,000 years. While some of these objects may break up during entry, most will reach the surface, forming craters if they strike on the land. On average, one ECA in this size range passes between the Earth and the Moon every few decades.

The proposed Spaceguard Survey deals effectively with this class of objects. Telescopes of 2- to 3-m aperture can detect them out to a distance of 200 million kilometers. Since their orbits bring them frequently within this distance of the Earth, a comprehensive survey will discover most of them

within a decade and can achieve near completeness within 25 years. Specifically, the survey modeled here, covering 6,000 square degrees of sky per month to magnitude $V = 22$, is calculated to achieve 91 percent completeness for potentially hazardous ECAs in 25 years. The most probable outcome of this survey will be to find that none of these objects will impact the Earth within the next century, although a few will need to be followed carefully to ensure that their orbits do not evolve into Earth-impact trajectories. In the unlikely case (chance much less than 1 percent) that one of these ECAs poses a danger to the Earth over the next century or two, there probably will be a warning of at least several decades to take corrective action to deflect the object or otherwise mitigate the danger.

2) **Comets**. Comets with short periods (less than 20 years) will be discovered and dealt with in the same manner as the ECAs described above; they constitute only about 1 percent of the ECA hazard in any case. However, comets with long periods (more than 20 years), many of which are entering the inner solar system for the first time, constitute the second most important impact hazard. While their numbers amount to only 5 to 10 percent of the ECA impacts, they approach the Earth with greater speeds and hence higher energy in proportion to their mass. It is estimated that about 25 percent of the objects reaching the Earth with energies in excess of 100,000 megatons are long-period comets. On average, one such comet passes between the Earth and Moon per century, and one strikes the Earth every few hundred thousand years.

Since a long-period comet does not (by definition) pass frequently near the Earth, it is not possible to obtain a census of such objects. Each must be detected on its initial approach to the inner solar system. Fortunately, comets are much brighter than asteroids of the same size, as a consequence of outgassing stimulated by solar heating. Comets in the size range of interest will generally be visible to the Spaceguard Survey telescopes by the time they reach the asteroid belt (500 million km distant), providing several months of warning before they approach the Earth. However, the short time-span available for observation will result in less well-determined orbits, and hence greater uncertainty as to whether a hit is likely; there is a greater potential for "false alarms" with

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comets than asteroids. Simulations carried out for this report indicate that only 35 percent of Earth-crossing intermediate- and long-period comets (ECCs) larger than 1 km diameter will be discovered with at least three months warning during the course of a survey centered on opposition and covering an area of 6,000 square degrees per month. By increasing the area of the survey to encompass the entire dark sky, as many as 77 percent of ECCs could be detected. A further gain in the detection completeness of ECCs could be achieved by increasing the telescope aperture so as to reach a limiting magnitude of $V = 24$. Because of the continuing hazard from Earth-crossing comets, which may appear at any time, a search for the cometary component of the Spaceguard survey should be continued even when the census of large Earth-crossing asteroids is essentially complete.

- 3) ***Smaller Asteroids, Comets, and Meteoroids*** (diameters from about 100 m to 1 km; energies from 20 to 100,000 megatons). Impacts by these bodies are below the energy threshold for global environmental damage, and they therefore constitute a smaller hazard in spite of their more frequent occurrence. Unlike the large objects, they do not pose a danger to civilization. The nature of the damage they cause depends on the size, impact speed, and physical nature of the impacting object; only a fraction of the projectiles in this size range will reach the surface to produce a crater. However, detonation either at the surface or in the lower atmosphere is capable of severe local damage, generally on a greater scale than that associated with a large nuclear weapon. Both the Tunguska (1908) and Meteor Crater impacts are small examples of this class. The average interval between such impacts for the whole Earth is a few centuries; between impacts in the inhabited parts of the planet is a few millennia; and between impacts in densely populated or urban areas is of the order of 100,000 years. About 300,000 Earth-crossing objects probably exist in this size range, with several passing between Earth and Moon each year.

The Spaceguard Survey will discover hundreds of objects in this size range every month. By the end of the initial 25-year survey, it will be possible to track the orbits of as many as 30,000, or about 10 percent of the total population. If the survey continues for a century, the total will rise to about 40 percent. Since the interval between such impacts is greater than 100 years, it is moderately likely that a continuous survey will detect the "next Tunguska" event with ample warning for

corrective action. However, in contrast to the larger ECAs and even the intermediate- and long-period comets, this survey will not achieve a near-complete survey of Earth-crossing objects in the 100-m size range in less than several centuries with current technology. If there is a societal interest in protecting against impacts of this size, presumably alternate technologies will be developed to deal with them.

9.2 SURVEY NETWORK: COST AND SCHEDULE

The proposed Spaceguard Survey network consists of six telescopes of 2- to 3-m aperture together with a central clearinghouse for coordination of the observing programs and computation of orbits. It also requires access to observing time on existing planetary radars and optical telescopes for follow-up. For purposes of this discussion, we assume that the Spaceguard Survey will be international in operations and funding, with the United States taking a leadership role through the Solar System Exploration Division of NASA's Office of Space Science and Applications.

9.2.1 *The Spaceguard Survey Telescopes*

The six survey telescopes required for the Spaceguard Survey are new instruments optimized for the discovery of faint asteroids and comets. While it is possible that one or more existing telescopes could be retrofitted for this purpose, we expect that the most cost-effective approach is to design and construct telescopes specifically for this project. For purposes of this Report, we consider a nominal telescope design of 2.5-m aperture and 5.2-m focal length with a refractive prime-focus corrector providing a field-of-view of at least 2 deg. The telescope will have altitude-azimuth mounting and be capable of pointing to an accuracy of a few arcsec and tracking to a precision of a fraction of an arcsec at rates up to 20 times sidereal. We assume that each telescope will be located at an existing observatory site of proven quality, so that no site surveys or new infrastructure development (roads, power, etc.) is required. The nominal aperture of 2.5 m is optimized for the ECA survey, but we note that larger telescope aperture (3 m or even more) would permit long-period comets to be detected at greater distances and thereby provide both greater completeness and months of additional warning.

An instrument of very similar design has recently been proposed by Princeton University for a wide-angle supernova survey. We believe that the Spaceguard Survey Telescopes could similarly be built for about \$6 million each, including observatory building, but not including the focal plane of several

mosaicked CCD detectors or the supporting data processing and computation capability. For each telescope, we allocate \$1 million for the focal plane and \$1 million for computer hardware and software, for a total cost per installation of \$8 million. If these six telescopes were purchased together, the capital costs would thus be about \$48 million.

For an estimate of operating costs, we assume that each telescope will require the following staffing: 2 astronomers, 2 administrative support personnel, 3 telescope operators, 1 each senior electronic and software engineers, and 2 maintenance and support technicians, for a total of 11 persons. Additional funds will be needed for transportation, power, sleeping accommodations for observers, and other routine costs associated with the operation of an observatory; the exact nature of these expenses depends on the location and management of the pre-existing site where the telescope is located. The total operations for each site should therefore run between \$1.5 million and \$2.0 million per year. In making this estimate we assume that each survey telescope is dedicated to the Spaceguard effort, and that it will be in use for about three weeks (100 to 150 hours) of actual observing per month. If it is intended that the telescope be used for other unrelated purposes when the Moon is bright, we assume that the other users will pay their *pro rata* share of operation costs.

The Spaceguard Survey Operations Center should provide overall coordination of the international observing effort, including rapid communications among the survey telescopes and those involved in follow-up observations. The Spaceguard Survey Operations Center will also compute orbits and ephemerides and provide an on-going evaluation of the hazard posed by any object discovered by the Survey. Similar functions are performed today for the much smaller number of known asteroids by the Minor Planet Center in Cambridge, Massachusetts. Scaling from that operation, we estimate an initial cost of \$2 million for computers and related equipment, and an annual operating cost of \$2 million.

A third component of the Spaceguard Survey Program is follow-up, including radar and optical observations. As noted previously in this Report, it would be desirable to have one or more dedicated planetary radars and large-aperture optical telescopes (4-m class). However, we anticipate that a great deal of useful work could be done initially using existing planetary radars and optical facilities. Therefore, for purposes of this Report, we simply allocate a sum of \$2 million per year for the support of radar and optical observing on these instruments.

9.2.2 Spaceguard Management and Cost-Sharing

The total estimated capital costs for the Spaceguard Survey are \$50 million, with operating costs of \$10 to \$15 million per year. We anticipate that these costs would be shared among several nations with advanced technical capability, with the maximum expenditure for the U.S. (or any other nation) of less than half the total amount. For purposes of U.S. budgeting, we assume that NASA will pay the cost of two telescopes (\$16 million) and the Operations Center (\$2 million), and will support operating costs of \$5 million per year.

Management of the U.S. component of the Spaceguard Survey could be accomplished by NASA in one of two ways. (1) The telescopes could be constructed and operated by universities or other organizations with funding from NASA Headquarters through grants or contracts, as is done today with the NASA IRTF telescope on Mauna Kea (owned by NASA but managed by the University of Hawaii under a five-year contract) or the 0.9-m Spacewatch Telescope on Kitt Peak (owned and operated by the University of Arizona with grant support from NASA). (2) NASA could construct and operate the telescopes itself through one of its Centers (JPL or Ames, for example); the Centers might contract with universities or industry for operations but would retain a more direct management control. Similarly, the Spaceguard Survey Operations Center could be located at a NASA Center or could be supported by grants or contracts at a university or similar location, such as the present Minor Planet Center at the Harvard-Smithsonian Center for Astrophysics. In any case, international cooperation and coordination is essential, and an international focus is required from the beginning in planning and supporting this program.

9.2.3 Initial Steps

The construction of the new Spaceguard Survey telescopes will require approximately four years from the time funding is available. In the meantime, several steps are essential to ensure a smooth transition from the present small surveys to the new program. (1) An international coordination effort should be initiated by NASA, independent of but coordinated with the International Astronomical Union Working Group on Near Earth Objects, in order to plan for the orderly development of the Spaceguard Survey network. (2) The small cadre of current asteroid observers should be strengthened. Additional expenditures of about \$1 million per year on existing teams would allow for expansion of personnel, purchase of badly needed new equipment, and greater sky coverage. Consequently, the discovery rate of ECAs should more than double, thereby also increasing our confi-

dence in modeling the population of such objects and planning the requirements for operation of the full-up survey. (3) In order to gain additional experience with the kind of automated CCD scanning techniques proposed for the Spaceguard Survey, efforts should be made as soon as possible to place in operation a telescope that utilizes these techniques; one such option is the proposed 1.8-m Spacewatch telescope at the University of Arizona. Efforts are also required in studying the use of CCD arrays and in developing appropriate software to support CCD scanning. (4) Continuing support should be provided for research on near-Earth asteroids and comets, including their dynamics and their physical properties. For purposes of this study, we assume an increase of \$2 million/year beyond current NASA expenditures for these programs, to be maintained during the transition period.

9.2.4 Proposed Schedule for NASA Funding

On the assumption that the Spaceguard Program can begin in a modest way in FY93 and will reach full funding about FY95, we suggest the following possible schedule for new NASA support of this effort.

Table 9-1. Proposed NASA Funding (in FY93 \$M).

Fiscal Year	93	94	95	96	97	98	99	00
Transition	02	02	02	02	02	02	01	00
Capital costs	01	02	04	04	04	03	00	00
Operations	00	00	00	01	02	03	05	05
Total	03	04	06	07	08	08	06	05

9.3 CONCLUSIONS

The Spaceguard Survey has been optimized for the discovery and tracking of the larger ECAs, which constitute the greater part of the cosmic impact haz-

ard. If any large ECAs threaten impact with the Earth, they almost certainly could be discovered with ample lead-time to take corrective action. The Spaceguard system also will discover most large incoming intermediate- and long-period comets, but the warning time may be only a few months. Finally, the great majority of the new objects discovered by the Spaceguard Survey will have diameters of less than 1 km; these should be picked up at a rate of about 500 per month. It is therefore reasonably likely that even the "next Tunguska" projectile (20 megatons energy) will be found by the Spaceguard Survey if it is continued for several centuries.

The Spaceguard Survey should be supported and operated on an international basis, with contributions from many nations. The total costs for this system are of the order of \$50 million in capital equipment, primarily for the six survey telescopes, and \$10 to \$15 million per year in continuing operating support. However, these estimates will vary depending on the aperture and detailed design of each telescope, the nature of the international distribution of effort, and the management of the survey. In particular, larger telescopes would be appropriate if greater emphasis is to be given to the search for long period comets. Whatever the exact cost, however, the proposed system can provide, within one decade of its initial operation, a reduction in the risk due to unforeseen impacts of about 50 percent at a relatively modest cost. Of course, additional and much greater expenditure would be required to deflect an incoming object if one should be discovered on an impact trajectory with the Earth, but in that unlikely event the cost and effort would surely be worth it. The first and essential step is that addressed by the Spaceguard Survey: to carry out a comprehensive survey of near-Earth space in order to assess the population of near-Earth asteroids and comets and to identify any potentially hazardous objects.

APPENDIX A.

ASTEROID TABLES

Table A1. Earth-crossing Asteroids. For each object whose orbit can evolve to intersect that of the Earth, the following information is given: the absolute magnitude (H), the approximate diameter, the depth interior to the Earth's orbit to which the asteroid can evolve, the orbital perihelion distance (q), semi-major axis (a), eccentricity (e), and inclination (i). The inclination is referred to the invariable plane of the solar system and each of these orbital elements represents a mean value at the time of Earth orbital crossing. P_s is the estimated probability of collision with the Earth (number per billion years) using the equations of Shoemaker et al. (1979) while P_o is the same probability calculated from the equations of E. J. Öpik (1951). V_i gives the approximate impact speed for an Earth collision. For some objects, it is not possible to compute mean orbital elements at the time of crossing and for these objects, osculating elements (given in parentheses) have been used as rough approximations. Where two sets of elements are given, there are two different conditions of crossing. For those objects whose motions are commensurate with Jupiter, no orbital elements are given because they have chaotic (unpredictable) motions over the long term. Those objects whose orbits are not sufficiently secure are probably lost and may be found only by a serendipitous search. These objects have an (L) following their name. This table is based upon the work of E. M. Shoemaker and is current through May 1991.

ATEN ASTEROIDS

Object			H	Approx. Diam (km)	Depth (AU)	q (AU)	a (AU)	e	i (deg)	P_s 10^9 yr	P_o 10^9 yr	V_i (km/s)
Provisional Designation	No.	Name										
1989 VA	—	—	17.00	1	—	0.292	0.729	(0.60)	(29)	—	(4)	(22)
1978 RA	2100	Ra-Shalom	16.05	2.4	0.388	0.445	0.832	0.465	13.1	6.3	6.7	17.9
1954 XA (L)	—	—	18.9	0.5	0.203	0.475	0.777	0.389	5.04	34	30	14.5
1984 QA	3362	Khufu	18.10	0.7	0.559	0.481	0.990	0.514	8.37	5.3	6.2	19.8
1976 UA	2340	Hathor	20.26	(0.2)	0.356	0.486	0.844	0.424	6.27	14	14	16.3
1986 TO	3753	—	14.4	3	—	0.499	0.998	(0.50)	(22)	—	(3)	(22)
1991 JY	—	—	16.50	2	0.204	0.572	0.940	0.391	44.3	2.9	2.4	26.7
1989 UQ	—	—	19.0	0.5	0.240	0.645	0.915	0.295	1.95	42	43	14.1
1990 VA	—	—	19.5	0.4	0.346	0.662	0.985	0.328	13.7	5.4	5.7	16.5
1986 EB	3554	Amun	15.82	2.0	0.299	0.730	0.974	0.251	21.6	5.4	5.0	17.4
1976 AA	2062	Aten	16.80	0.9	0.223	0.743	0.966	0.231	18.0	7.1	6.5	16.0

APOLLO ASTEROIDS

Object			H	Approx Diam	Depth	q	a	e	i	P _s	P _o	V _i
Provisional Designation	No.	Name		(km)	(AU)	(AU)	(AU)		(deg)	10 ⁹ yr	10 ⁹ yr	(km/s)
1983 TB	3200	Phaethon	14.60	6.9	—	0.140	1.271	(0.89)	(22)	—	(1.4)	(35)
1949 MA	1566	Icarus	16.40	0.9	0.844	0.205	1.078	0.810	18.0	1.8	2.2	30.6
1978 SB	2212	Hephaistos	13.87	5	0.929	0.240	2.163	0.889	10.0	0.44	1.2	34.6
1990 UO (L)	—	—	20.5	0.2	0.771	0.276	1.234	0.776	24.1	0.9	1.4	30.5
1990 SM	—	—	16.5	1	0.727	0.395	2.157	0.817	11.3	0.4	1.1	30.0
1974 MA (L)	—	—	14.0	5	—	0.973	1.757	0.446	53.4	0.9	2.5	32.0
								0.772	32.8			
5025 P-L(L)	—	—	15.9	2	—	0.420	(4.2)	(0.90)	(6.2)	—	(~1)	(32)
1984 KB	—	—	15.5	1.4	0.760	0.429	2.221	0.807	3.37	1.1	3.2	28.8
1986 WA	3838	Epona	15.4	3	—	0.452	1.505	(0.70)	(29)	—	(1)	(29)
1991 AM	—	—	16.5	1	0.613	0.454	1.695	0.732	19.7	0.5	1.0	28.0
1991 AQ	—	—	17.5	1	—	0.500	2.159	(0.77)	(3.2)	—	(4)	(27)
1947 XC	2201	Oljato	15.25	1.4	0.657	0.511	2.174	0.765	1.33	2.3	6.1	26.4
1936 CA	2101	Adonis	18.70	1	0.620	0.512	1.875	0.727	2.03	2.8	6.2	25.4
1971 UA	1865	Cerberus	16.84	1.0	0.504	0.526	1.080	0.513	14.9	2.5	3.1	20.9
1971 FA	1864	Daedalus	14.85	(3.1)	0.491	0.526	1.461	0.640	15.9	1.0	1.6	26.0
1982 TA	4197	—	14.5	1.8	—	0.529	2.300	(0.77)	(12)	—	(1)	(27)
1990 BG	—	—	14.0	5	0.409	0.544	1.486	0.634	26.3	0.6	1.1	26.3
1985 PA	3752	Camillo	15.5	2	—	0.551	1.414	(0.61)	(32)	—	(1)	(27)
1987 SY	4450	Pan	17.1	1	0.522	0.555	1.442	0.615	1.85	6.4	10.5	22.2
1979 XB (L)	—	—	19.0	0.5	(0.56)	0.566	2.264	(0.75)	(10)	(0.5)	(1.2)	(25)
1989 PB	4769	Castalia	16.9	1.5	0.478	0.568	1.063	0.466	9.68	4.2	5.1	18.9
1990 MU	4953	—	14.3	3	0.487	0.569	1.622	0.649	26.4	0.6	0.9	26.5
1991 CB1(L)	—	—	18.0	1	0.484	0.580	1.686	0.656	9.36	1.2	2.1	23.4
1987 KF	4341	Poseidon	15.6	3	0.512	0.593	1.836	0.677	5.87	1.5	2.9	23.3
1986 PA	4034	—	18.1	1	0.438	0.606	1.060	0.428	10.0	4.5	5.3	18.0
1937 UB (L)	—	—	17.0	1	0.459	0.624	1.639	0.619	5.64	2.2	3.7	21.7
1989 QF	—	—	18.0	1	0.418	0.639	1.155	0.447	5.27	6.4	8.1	17.9
1987 OA	—	—	18.5	1	0.414	0.641	1.490	0.570	11.0	1.6	2.4	21.1
1932 HA	1862	Apollo	16.25	1.4	0.423	0.647	1.471	0.560	6.13	2.8	4.3	20.3
1988 EG	—	—	19.0	1	0.399	0.664	1.270	0.477	2.71	8.8	12	18.3
1990 TG1	—	—	15.0	3	—							
1989 UR	—	—	18.0	1	0.362	0.675	1.080	0.375	11.5	4.4	5.1	17.1
1989 FC	4581	Asclepius	20.5	0.2	0.371	0.679	1.023	0.336	4.41	13.3	15.1	15.4
1959 LM	4183	Cuno	14.5	4	0.425	0.699	1.981	0.647	7.42	1.3	2.2	21.3
1991 GO (L)	—	—	19.0	0.5	0.380	0.706	1.930	0.634	9.55	1.1	1.9	21.2
1991 BA (L)	—	—	28.5	0.006	—	0.713	2.161	(0.67)	(2.2)	—	(5)	(21)
1977 HB	2063	Bacchus	16.4	1	0.330	0.719	1.078	0.333	8.99	6.5	7.2	15.8
1989 DA	—	—	18.0	1	0.602	0.728	2.166	0.664	5.08	1.5	2.8	20.8
1973 EA	1981	Midas	15.0	1	—	0.735	1.776	0.586	5.5	3.8	0.7	30.7
								0.652	41.3			
1983 VA	—	—	16.5	2	0.485	0.737	2.615	0.718	6.81	0.7	1.6	21.6
1990 HA	—	—	17.0	1	0.599	0.747	2.567	0.709	3.94	1.1	2.7	21.1
1990 UA	—	—	19.50.4	0.373	0.750	1.721	0.564	0.81	8.3	12.9	18.8	
1989 FB	4544	Xanthus	7.1	1	0.250	0.761	1.042	0.270	13.3	6.6	6.4	15.5
1948 OA	1685	Toro	14.23	5.2	—	0.769	1.368	0.438	9.15	(4)	(4.2)	17.2

APOLLO ASTEROIDS (Cont'd.)

Object			H	Approx Diam	Depth	q	a	e	i	P _s	P _o	V _i
Provisional Designation	No.	Name		(km)	(AU)	(AU)	(AU)		(deg)	10 ⁹ yr	10 ⁹ yr	(km/s)
1988 XB	—	—	17.5	1	0.263	0.779	1.467	0.469	3.98	6.2	7.9	17.0
1950 DA (L)	—	—	15.8	2	0.266	0.783	1.683	0.535	10.7	1.9	2.4	18.7
1978 CA	—	—	17.8	1.9	0.293	0.784	1.125	0.303	25.5	3.6	3.0	19.5
1988 TA	—	—	21.0	0.2	0.262	0.789	1.541	0.488	3.42	6.3	8.2	17.1
1990 UQ	—	—	17.5	1	0.262	0.789	1.551	0.491	3.76	5.8	7.5	17.2
1988 VP4	—	—	15.8	3	0.328	0.790	2.263	0.651	10.3	1.0	1.5	20.1
1973 NA (L)	—	—	15.5	3	—	0.803	2.447	0.672	67.9	0.5	0.4	40.5
								0.891	51.8			
1990 UN (L)	—	—	23.5	0.06	0.363	0.808	1.709	0.527	3.42	5.3	7.0	17.4
1951 RA	1620	Geographos	15.60	2	0.210	0.808	1.245	0.351	14.2	3.8	3.9	16.7
1987 SB	4486	Mithra	15.4	3	0.595	0.813	2.202	0.631	1.06	5.5	8.8	18.5
1977 HA	2135	Aristaeus	17.94	1	—	0.816	1.600	(0.49)	(23)	(2.0)	(1.5)	(21)
6344 P-L(L)	—	—	21.9	0.1	0.207	0.822	2.619	0.686	3.71	—	1.6	19.1
1982 HR	3361	Orpheus	19.03	0.8	—	0.822	1.209	(0.32)	(2.7)	—	(21)	(14)
1990 SP	—	—	17.0	1	—	0.827	1.355	(0.39)	(13)	—	(4)	(17)
6743 P-L	5011	—	17.0	1	0.224	0.837	1.635	0.488	6.88	3.8	4.5	16.7
1991 EE	—	—	17.5	1	—	0.838	2.266	(0.63)	(10)	—	(2)	(19)
1991 BB	—	—	16.0	2	—	0.866	1.186	(0.27)	(39)	—	(3)	(24)
1991 DG	—	—	18.5	0.6	0.175	0.870	1.427	0.390	11.0	4.4	4.4	15.8
1990 OS	—	—	20.0	0.3	0.251	0.878	1.672	0.475	0.86	17.2	19.3	15.5
1991 BN (L)	—	—	20.0	0.3	0.168	0.885	1.443	0.387	7.58	6.4	6.5	15.0
1990 SS	—	—	19.0	0.6	—	0.886	1.703	(0.48)	(19)	—	(2)	(19)
1975 YA	2102	Tantalus	15.3	2	—	0.888	1.290	0.312	62.5	2.5	1.5	34.8
								0.744	49.1			
1989 JA	—	—	16.5	2	0.158	0.893	1.769	0.495	14.8	2.8	2.3	17.5
1986 JK	—	—	19.0	1	—					—	—	—
1983 LC (L)	—	—	19.0	0.5	0.334	0.904	2.629	0.656	1.54	5.8	7.6	16.8
1991 JW	—	—	19.5	0.5	0.104	0.913	1.038	0.120	8.34	30.0	28.9	12.6
1991 CS	—	—	17.5	1	—	0.932	1.123	(0.17)	(37)	—	(5)	(22)
1989 AZ	—	—	19.5	0.4	0.138	0.935	1.649	0.433	9.92	5.9	5.0	15.1
1987 QA	4257	Ubasti	15.8	3	—	—	—	—	—	—	—	—
1990 MF	—	—	18.7	0.6	0.163	0.949	1.747	0.457	3.02	16.6	15.2	14.1
1948 EA	1863	Antinous	15.54	1.8	0.076	0.951	2.260	0.579	23.1	—	1.3	19.9
1979 VA	4015	—	15.99	5	0.074	0.955	2.645	0.639	5.03	—	0.84	15.5
1981 VA	3360	—	16.20	1.8	0.346	0.958	2.462	0.611	38.6	0.7	1.6	26.6
								0.751	20.8			
1982 DB	4660	Nereus	18.30	1	0.092	0.969	1.490	0.350	4.87	22.5	20.3	13.1
1982 BB	3103	—	15.38	1.5	0.054	0.974	1.407	0.308	22.0	—	3.9	17.3
1989 UP	—	—	20.7	0.2	—	0.988	1.864	(0.47)	(3.9)	—	(13)	(14)
1989 AC	4179	Toutatis	14.0	5	—					—	—	—
1976 WA	2329	Orthos	14.9	3	0.295	0.990	2.404	0.588	32.6	1.8	2.2	23.3
								0.702	16.9			
1991 JX	—	—	18.5	0.6	—					—	—	—
1984 KD	3671	Dionysus	16.3	1	—	1.011	2.198	(0.54)	(14)	—	(1.5)	(16)
1989 VB	—	—	20.0	0.3	—	1.026	1.865	(0.45)	(1.6)	—	(13)	(13)

EARTH-CROSSING AMOR ASTEROIDS

Object			H	Approx Diam	Depth	q	a	e	i	P _{1^s}	P _{1^o}	V ₁
Provisional Designation	No.	Name		(km)	(AU)	(AU)	(AU)		(deg)	10 ⁹ yr	10 ⁹ yr	(km/s)
1982 DV	3288	Seleucus	15.0	2.8	0.319	0.709	2.032	0.651	5.46	—	1.4	21.0
1980 WF	4688	—	18.6	0.6	0.299	0.730	2.231	0.673	5.38	—	1.1	20.9
1988 SM	—	—	18.0	1	—	—	—	—	—	—	—	—
1918 DB	887	Alinda	13.76	4.2	—	—	3:1 commensurability		—	—	—	—
1978 DA	2608	Seneca	17.52	0.9	—	—	3:1 commensurability		—	—	—	—
1991 FA	—	—	17.5	1	0.262	0.766	2.164	0.646	4.51	—	1.7	19.8
1991 FB	—	—	18.5	0.5	0.218	0.810	2.356	0.656	10.0	—	0.84	19.7
1991 FE	—	—	14.9	4	0.116	0.912	2.451	0.628	3.54	—	1.6	16.4
1980 PA	3908	—	17.4	1	0.090	0.938	1.926	0.513	2.80	—	4.0	14.7
1987 WC	—	—	19.5	0.4	—	—	—	—	—	—	—	—
1991 DB	—	—	18.5	0.6	0.079	0.949	1.720	0.448	14.2	—	3.1	16.0
1950 KA	1580	Betulia	14.52	7.4	(0.27)	0.957	2.196	0.564	48.5	0.50	1.7	30.6
								0.792	26.4			
1981 QB	4596	—	16.0	2	0.064	0.963	2.240	0.570	28.5	—	0.75	21.8
1932 EA1	1221	Amor	17.7	1	0.061	0.966	1.921	0.497	12.0	—	1.5	15.4
1990 VB	—	—	16.0	2	0.058	0.970	2.444	0.603	18.5	—	0.34	18.1
1960 UA	2061	Anza	16.56	(2.7)	0.050	0.978	2.263	0.568	3.41	—	1.3	14.2
1968 AA	1917	Cuyo	13.9	3	0.051	0.978	2.149	0.545	19.3	—	1.3	17.8
1982 XB	3757	—	18.95	0.5	0.046	0.981	1.838	0.466	2.55	—	5.1	13.4
1929 SH	1627	Ivar	13.20	8.1	0.042	0.986	1.863	0.471	7.98	—	1.8	14.0
1973 EC	1943	Anteros	15.75	1.8	0.041	0.987	1.431	0.310	9.86	—	3.5	13.4
1983 RD	3551	—	16.75	0.9	—	—	—	—	—	—	—	—
1953 EA	1915	Quetzalcoatl	18.97	0.3	—	—	3:1 commensurability		—	—	—	—
1987 SF3	—	—	19.0	0.5	0.039	0.989	2.252	0.561	3.56	—	1.1	13.9
1991 JR (L)	—	—	22.5	0.1	0.038	0.991	1.407	0.296	10.3	—	5.7	13.4
1981 ET3	3122	—	14.2	4	0.036	0.992	1.768	0.439	20.0	—	2.1	17.0
1987 QB	—	—	19.0	0.5	0.021	1.006	2.795	0.640	2.34	—	0.26	14.7
1985 WA	—	—	19.0	0.5	—	—	5:2 commensurability		—	—	—	—
1972 RA	2202	Pele	16.8	2	0.018	1.010	2.291	0.559	8.70	—	0.10	14.8
1980 AA	—	—	19.5	(0.5)	0.009	1.020	1.892	0.461	3.55	—	0.30	13.2
1986 LA	3988	—	18.3	1	-0.002	1.026	1.545	0.336	13.4	—	—	—
1986 DA	—	—	16.0	2.3	—	—	5:2 commensurability		—	—	—	—
1986 RA	—	—	16.0	4	—	—	2:1 commensurability		—	—	—	—

Table A2. Asteroids discovered between May and December 1991 whose orbits can evolve to intersect that of the Earth. Osculating orbital elements are given.

ATEN ASTEROID

Provisional Designation	H	Approx. Diam. (km)	q (AU)	e	a (AU)
1991 VE	19.5	0.4	0.337	0.617	0.880

APOLLO ASTEROIDS

Provisional Designation	H	Approx. Diam. (km)	q (AU)	e	a (AU)
1991 RC	17.0	1	0.185	0.829	1.082
1991 LH	17.0	1	0.364	0.731	1.352
1991 TB2 (L?)	17.0	1	0.394	0.836	2.397
1991 VL	14.0	5	0.419	0.771	1.834
1991 WA	17.0	1	0.564	0.643	1.578
1991 RB	19.0	0.5	0.749	0.484	1.450
1991 VK	16.5	2	0.911	0.506	1.842
1991 VA (L)	27.0	0.01	0.926	0.351	1.426
1991 TB1	17.0	1	0.942	0.353	1.455
1991 TU (L)	28.5	0.005	0.945	0.333	1.416
1991 TF3 (L?)	19.0	0.5	0.957	0.531	2.042
1991 VG	28.8	0.001	0.973	0.075	1.051
1991 VH	17.0	1	0.973	0.145	1.138
1991 XA (L)	23.5	0.05	0.979	0.571	2.283
1991 TT (L)	26.0	0.02	1.002	0.161	1.193

EARTH-CROSSING AMOR ASTEROID

Provisional Designation	H	Approx. Diam. (km)	q (AU)	e	a (AU)
1991 OA	18.0	1	1.036	0.587	2.508

Table A3. Short period comets whose periods (P) are less than 20 years and whose perihelion distances (q) are less than 1.1 AU. Because their motions are often chaotic, it is difficult to predict whether the orbit of a periodic comet can evolve to intersect the Earth's orbit. However, the following comets either could have made, or can make, close Earth approaches. The listed osculating orbital elements are appropriate for the latest observed perihelion passages (T). The orbital eccentricity (e) is followed by the argument of perihelion (Peri), the longitude of the ascending node (Node) and the inclination (Incl). The angular elements are referred to the ecliptic plane and the B1950.0 equinox.

Comet	T	P	q	e	Peri	Node	Incl
Machholz	1991.55	5.24	0.126	0.958	14.5	93.8	60.1
Encke	1990.82	3.28	0.331	0.850	186.2	334.0	11.9
Helfenzrieder	1766.32	4.35	0.406	0.848	178.7	75.6	7.9
Honda-Mrkos-Pajdušáková	1990.70	5.30	0.541	0.822	325.7	88.7	4.2
Brorsen	1879.24	5.46	0.590	0.810	14.9	102.3	29.4
Lexell	1770.62	5.60	0.674	0.786	224.9	133.9	1.6
Denning-Fujikawa	1978.75	9.01	0.779	0.820	334.0	41.0	8.7
Biela	1852.73	6.62	0.861	0.756	223.2	247.3	12.6
Blanpain	1819.89	5.10	0.892	0.699	350.2	79.2	9.1
Schwassmann-Wachmann 3	1990.38	5.35	0.936	0.694	198.8	69.3	11.4
Hartley 2	1991.70	6.26	0.953	0.719	174.9	226.1	9.3
Grigg-Skjellerup	1987.46	5.10	0.993	0.665	359.3	212.6	21.1
Tuttle	1980.95	13.7	1.015	0.823	206.9	269.9	54.5
Giacobini-Zinner	1992.28	6.61	1.034	0.706	172.5	194.7	31.8
Tuttle-Giacobini-Kresák	1990.11	5.46	1.068	0.656	61.6	140.9	9.2
Wirtanen	1991.72	5.50	1.083	0.652	356.1	81.6	11.7
Finlay	1988.43	6.95	1.094	0.699	322.2	41.7	3.6

Table A4. Close Earth approaches by asteroids and comets (< 0.2 AU) during the interval January 1992 to December 2000. This list includes only those objects known to have secure orbits in December 1991.

Provisional Designation	Object		Date of Close Approach (mm/dd/yy)	Minimum Separation (AU)	Minimum Separation (Lunar Distance)	Approx. Diameter (km)
	No.	Name				
1973 EA	1981	Midas	3/11/92	0.134	52.4	1
1989 AC	4179	Toutatis	12/08/92	0.024	9.4	5
1989 PB	4769	Castalia	4/08/93	0.132	51.6	1.5
1982 HR	3361	Orpheus	3/02/94	0.150	58.7	0.
1990 MU	4953	—	5/30/94	0.142	55.6	3
1951 RA	1620	Geographos	8/25/94	0.033	12.9	
1978 RA	2100	Ra-Shalom	10/12/94	0.155	60.6	2.
1976 AA	2062	Aten	1/12/95	0.127	49.7	0.9
1976 UA	2340	Hathor	1/16/95	0.137	53.6	0.2
		P/Honda-Mrkos-				
		Pajdušáková	2/04/96	0.170	66.5	—
1991 JX	—	—	6/08/95	0.034	13.3	0.4
1977 HB	2063	Bacchus	3/31/96	0.068	26.6	1
1949 MA	1566	Icarus	6/11/96	0.101	39.5	0.9
1982 BB	3103	—	8/06/96	0.115	45.0	1.5
1982 TA	4197	—	10/25/96	0.085	33.3	1.8
1980 PA	3908	—	10/27/96	0.061	23.9	1
1989 AC	4179	Toutatis	11/29/96	0.035	13.7	5
		P/Encke	7/04/97	0.190	74.3	—
1984 KD	3671	Dionysus	7/06/97	0.114	44.6	1
1978 RA	2100	Ra-Shalom	9/26/97	0.171	66.9	2.4
1975 YA	2102	Tantalus	12/21/97	0.138	54.0	2
1982 HR	3361	Orpheus	2/12/98	0.167	65.3	0.8
1988 EG	—	—	2/28/98	0.032	12.5	1
1971 UA	1865	Cerberus	11/24/98	0.163	63.8	1.0
1948 EA	1863	Antinous	4/01/99	0.190	74.3	1.8
1991 JX	—	—	6/02/99	0.050	19.6	0.6
1986 JK	—	—	7/11/00	0.122	47.7	1
1987 SB	4486	Mithra	8/14/00	0.047	18.4	3
1978 RA	2100	Ra-Shalom	9/06/00	0.190	74.3	2.4
1976 UA	2340	Hathor	10/25/00	0.197	77.1	0.2
1989 AC	4179	Toutatis	10/31/00	0.074	29.0	5
1959 LM	4183	Cuno	12/22/00	0.143	56.0	4

Source: D. Yeomans

APPENDIX B

GLOSSARY

A

absolute magnitude (of asteroid)	the magnitude an asteroid would have at zero phase angle and at 1 AU from the Earth and Sun.
Amor asteroid	asteroid having perihelion distance between 1.017 and 1.3 AU. Amor asteroids do not cross the Earth's orbit at the present time.
aperture (telescope)	the diameter of the primary lens or mirror of a telescope; hence, the best single measure of the light-gathering power of a telescope.
aphelion	the point in an elliptical orbit of a planet, asteroid, or comet that is farthest from the Sun.
Apollo asteroid	asteroid having semimajor axis greater than or equal to 1.0 AU and perihelion distance less than or equal to 1.017 AU. Apollo asteroids cross the Earth's orbit at the present time.
arcminute	minute of arc, equal to 1/60 degree.
arcsecond	second of arc, equal to 1/3600 degree.
asteroid	an object orbiting the Sun that is smaller than a major planet (sub-km to about 1,000 km diameter), but shows no evidence of an atmosphere or other types of activity associated with comets. Most asteroids are located in a belt between Mars and Jupiter from 2.2 to 3.3 AU from the Sun.
astrometry	precision measurement of position and/or velocity for an astronomical object.
astronomical unit (AU)	average distance between the Earth and the Sun, equal to about 150 million km.
Aten asteroid	asteroid having semimajor axis less than 1.0 AU and aphelion distance greater than 0.983 AU.

C

CCD	charge-coupled device. A solid-state detector used for low-light-level imaging.
comet	a volatile-rich body that develops a transient atmosphere as it orbits the Sun. The orbit is usually highly elliptical or even parabolic (average perihelion distance less than 1 AU; average aphelion distance, roughly 10^4 AU). When a comet comes near the Sun, some of its material vaporizes, forming a large head of tenuous gas, and often a tail.

D

declination	angular distance north or south of the celestial equator.
Doppler effect	apparent change in frequency or wavelength of the radiation from a source due to its relative motion in the line of sight.

E	
ECA	Earth-crossing asteroid. An asteroid whose orbit crosses the Earth's orbit or will at some time cross the Earth's orbit as it evolves under the influence of perturbations from Jupiter and the other planets.
ECC	Earth-crossing comet. A comet whose period is greater than 20 years and perihelion distance is less than 1.017 AU.
eccentricity (of ellipse)	the measure of the degree to which an ellipse is not circular; ratio of the distance between the foci to the major axis.
ecliptic	the apparent annual path of the Sun on the celestial sphere.
ephemeris	(pl., ephemerides) a list of computed positions occupied by a celestial body over successive intervals of time.
I	
inclination (of orbit)	the angle between the orbital plane of a comet or asteroid and the ecliptic plane.
intermediate-period comet	comet with a period of 20 to 200 years.
K	
kiloton	energy equivalent to 1,000 tons of TNT (4.3×10^{12} Joules).
Kirkwood gaps	regions in the asteroid zone which have been swept clear of asteroids by the perturbing effects of Jupiter. They were named for the American astronomer Daniel Kirkwood, who first noted them in 1866.
L	
long-period comet	comet with a period greater than 200 years.
M	
magnitude (astronomical)	a number, measured on a logarithmic scale, used to indicate the brightness of an object. Two stars differing by 5 magnitudes differ in brightness by a factor of 100. The brighter the star, the lower the numerical value of the magnitude; very bright objects have negative magnitudes. The star Vega (alpha Lyrae) is defined to be magnitude zero.
main-belt asteroids	asteroids that occupy the main asteroid belt between Mars and Jupiter, sometimes limited specifically to the most populous parts of the belt, from 2.2 to 3.3 AU from the Sun.
megaton	energy equivalent of one million tons of TNT (4.3×10^{16} Joules).
meteor	the light phenomenon produced by an object experiencing frictional heating when entering a planetary atmosphere; also used for the glowing meteoroid itself. If particularly large, it is described as a fireball.
meteorite	a natural object of extraterrestrial origin that survives passage through the atmosphere.

N

NEO near-Earth object. Objects whose orbits bring them near the Earth. Specifically Apollo, Amor, and Aten Asteroids, and certain comets.

new comet comet on its first approach to the Sun.

O

Oort comet cloud a spherical cloud of comets having semimajor axes greater than 20,000 AU. Comets in this shell can be sufficiently perturbed by passing stars or giant molecular clouds so that a fraction of them acquire orbits that take them within the orbits of Jupiter and Saturn.

opposition an angle of 180° between a planet, the Earth, and the Sun.

P

perihelion the place in the orbit of an object revolving around the Sun where it is closest to the Sun.

perturbation for a body orbiting the Sun or a planet, the gravitational effect of a third body (e.g., another planet) on its orbit, usually resulting in small changes or periodic fluctuations.

phase angle the solar phase angle: the angle subtended at the center of a planet or other body by the directions to the Sun and the observer.

power law a mathematical relation in which the resulting value is dependent upon a variable being raised to an exponential power.

R

resonance an orbital condition in which one object is subject to periodic gravitational perturbations by another, most commonly arising when two objects orbiting a third have periods of revolution that are simple multiples or fractions of each other.

right ascension a coordinate for measuring the east-west positions of celestial bodies; the angle measured eastward along the celestial equator from the vernal equinox to the hour circle passing through a body.

S

Schmidt telescope a type of reflecting telescope (more accurately, a large camera) in which the coma produced by a spherical concave mirror is compensated for by a thin correcting lens placed at the opening of the telescope tube. The Palomar 1.2-m Schmidt has a usable field of 6° .

semimajor axis (of orbit) half the major axis of an ellipse. For a planetary orbit, it represents the body's average distance from the Sun.

short-period comet comet with a period less than 20 years.

sidereal period the time it takes for a planet or satellite to make one complete revolution relative to the stars.

steradian the solid angle which, having its vertex in the center of a sphere, cuts out an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere. A sphere contains 4π steradians.

APPENDIX C

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