N91-33030
S13-85
20085
P-20

Benefits to the Nation from Astronomy and Astrophysics

KEY POINTS

- Astronomy makes unexpectedly large contributions to formal and informal science education, given the small number of research astronomers.
- Technology transfer and spin-offs from astronomy have important applications in medicine, industry, defense, environmental monitoring, and consumer products.
- Mankind's view of its place in the world as a whole is strongly influenced by the results of astronomical research.
- Astronomy provides unusually promising opportunities for international cooperation.
- Other sciences benefit from synergistic interactions with astronomy.

I. INTRODUCTION

Astronomy and astrophysics could not exist in their present form in this country without firm public support, expressed through the funding of research by federal and other agencies, public and private. The providers of this support can quite reasonably ask what they are getting in return for their money. The primary answer is, of course, scientific knowledge and all that it implies. (Identifying how that knowledge can best be extended in the future was the principle task of the Astronomy and Astrophysics Survey Committee (AASC)). But there are other, less obvious, returns, and the Panel on Astronomy and Astrophysics as National Assets was charged with identifying and documenting these.

It is not the intention to claim that these educational, cultural, and technological spin-offs are the sole, or even the major, justification for astronomical research, but only that they are a real part of the total picture of how science interacts with the rest of society. In addition, because astronomical objects and ideas are relatively appealing to non- scientists, it seems plausible that the subject may be able to play a significant role in the essential task of revitalizing American leadership in science and technology, both by encouraging young people to consider careers in these areas and by promoting scientific awareness among the general public.

The chapter on National Assets in Volume I of the AASC report presents an overview of the synergistic, educational, and cultural contributions of astronomy and astrophysics. This panel report includes a number of additional examples and technical details of a few outstanding ones. Space did not permit including all of the items collected by the panel or complete crediting of the information to the colleagues who provided it, though contributors other than panel members are listed at the end of the chapter.

II. SCIENCE EDUCATION AND LITERACY

The need for a scientifically sophisticated electorate and how far we are from achieving this have received enough publicity in recent years to require no further explication here. But, of the little science that most people are exposed to–and that they choose to expose themselves to–astronomy forms a surprisingly large part. People trained in astronomy also form part of the general technologically-educated manpower pool.

A. Formal Education

1. College-level courses

Formal astronomy classes have their largest impact at the non-major undergraduate level. The college and universities with astronomy (or physics and astronomy) departments had 1.2 million undergraduates in 1988; 103,300 of them were taking introductory astronomy (Ellis 1988). This means that (integrated over a 4.5- year average curriculum) 35-40 percent of the graduates of these institutions fulfill their science breadth requirements with astronomy, generally as their only exposure to physical science. Astronomers typically make up 5-10 percent of the physical science faculties at these institutions.

There is also considerable demand for astronomy at colleges with no separate department of the subject. Each year the American Astronomical Society receives more than 100 requests for visits by research astronomers to these institutions through its Shapley Program. About 90 requests can be filled. The primary purpose is to talk with classes and student groups, but most visits include a public lecture and meetings with administrators well (C.R. Tolbert, University of Virginia, personal communication 1990). Text book sales indicate that a total of 200-250,000 students per year enroll in an astronomy course (M. Zeilik, University of New Mexico, personal communication 1990).

While taking these classes, students both increase their knowledge of the specific subject and change their attitudes toward science in general. A standardized test, administered as part of the planning for Project STAR (Section II.A.2), shows that those who complete an introductory class know about as much astronomy as the average secondary school teacher. Those just starting the class do considerably less well and score at about the same level as elementary school teachers.

Attitudes toward science were probed with an anonymous questionnaire given to undergraduates at Cornell University, University of Maryland, and University of Wisconsin at the end of one-semester courses. Table 1 shows the results. More than 70 percent of the 1260 students polled reported that they thought understanding science was more important than they had at the beginning of the semester. The majority also said that they were more likely to read about science and to vote for pro-science candidates for political office. All but a few percent of the rest reported their views as unchanged (some explicitly volunteering the information that they had been fairly pro- science to begin with).

Most university departments also offer adult education and extension courses in astronomy and report (e.g., from UCLA and Harvard) that these are among the most popular and successful of their offerings.

2. Pre-College Education and Teacher Training

After prolonged near-absence, astronomy is beginning to reappear in elementary and high school curricula. The 1989 National Science Foundation's (NSF) grants for astronomy education included two high school student summer programs; one each for teachers in high schools, two-year colleges, and elementary and middle schools; and three projects to develop teaching materials for middle and high schools. Many other programs are supported by schools, colleges, and research organizations. A representative sampling follows.

The Astronomical Society of the Pacific "Universe in the Classroom" one-week summer workshop for grade 3-12 educators has had 2500 alumni over the past 12 years. The Society also provides a catalog of educational materials to about 250,000 people world-wide; and a newsletter "Universe in the Classroom" goes to 22,000 teachers, with further reproduction by school districts and planetariums and translation into five foreign languages.

The Space Telescope Science Institute (StScI) currently supplies speakers on request to school classes in its area at a rate of about one per day. Astronomers at nearly every university, lab, and observatory talk to grade and high school classes and clubs on a regular basis.

TABLE 1. CHANGES IN STUDENT ATTITUDES TOWARD SCIENCE DURING ONE-SEMESTER INTRODUCTORY ASTRONOMY COURSES

Understanding science is:		Understanding science is:	
Much easier*	131 (10.4%)	Much more important*	385 (30.7%)
Somewhat easier	495 (39.4%)	Somewhat more important	513 (40.8%)
About the same	533 (42.4%)	About the same	541 (27.1%)
Somewhat harder	80 (6.4%)	Somewhat less important	14 (1.1%)
Much harder	22 (1.8%)	Much less important	3 (0.2%)
Probability of reading about science in the future		**Probability of voting for candidates favoring support for scientific research**	
Much higher*	258 (20.5%)	Much higher*	303 (24.1%)
Somewhat higher	593 (47.2%)	Somewhat higher	478 (38.0%)
About the same	375 (29.8%)	About the same	445 (35.4%)
Somewhat lower	17 (1.4%)	Somewhat lower	19 (1.5%)
Much lower	14 (1.1%)	Much lower	12 (1.0%)

* Number of students expressing this opinion after a one semester introductory astronomy course.

StScI also participates in (1) a summer workshop for science teachers that is expected to have about 300 participants from across the nation in 1990, (2) enrichment programs for scientifically-interested high school students from under-represented minorities, and (3) production of a 32-part instructional television series for middle schools, with broadcast in Maryland and elsewhere to begin in fall 1990.

SPICA at the Center for Astrophysics is an unusually highly- leveraged project whose participants, secondary school teachers, in turn present workshops for elementary and junior high teachers in their home districts.

The National Radio Astronomy Observatory (NRAO) in cooperation with West Virginia University operates a summer workshop for high school teachers, whose funding for 1990 is being taken over by the Claude Worthington Benedum Foundation from NSF.

The Naval Research Laboratory (NRL) and six other Washington-area research institutions provide opportunities for about 100 high school students a year to get involved in astronomical research. Most go on to careers in science and engineering.

More than 500 Starlab portable planetariums (16-foot inflatable domes from Learning Technologies, Cambridge, Massachusetts) have reached some five million school children (mostly in the earlier grades, and including many inner city and disadvantaged kids)

At the Thacher School Summer Science Program, about 1000 students over the past 30 years have worked on an astronomical research project (determining asteroid orbits from photographs and mastering the necessary associated math and physics). All participants go on to college. About 37 percent of the pre-1985 graduates are now working in science and medicine, and 34 percent in engineering, mathematics, and computer science (including the founder of Lotus Development Corporation).

Haystack Observatory has a similarly-successful summer internship for middle school students and the University of Illinois has one for high school students.

Six inner-city San Antonio schools are pioneering a junior- level year of high school science consisting of astronomy and marine biology as part of Project 2061. The real surprise is that most of the students have chosen to take another year of science as an elective in their senior years.

Project STAR (Science Through its Astronomical Roots), one of the most extensive NSF-funded programs, is being developed at the Center for Astrophysics as a serious, quantitative alternative to high school chemistry and physics.

Many of these projects were initiated within the astronomical community, and all have had some input from researchers. But this is an area where more can and should be done. Specific initiatives are proposed by other panels. It is at the high school level and earlier that science must be made attractive to students, before they decide not to take the necessary mathematics.

B. Informal Education and Scientific Literacy

The activities discussed here have three connections with astronomical and other scientific research. First, virtually all of them have either been initiated by or had significant input from research-oriented astronomers. Second, many lines of anecdotal evidence indicate that informal exposure to astronomy motivates people to take a serious interest in science and technology as potential careers. And, finally, in order for books, television programs, planetarium shows, and other presentations about astronomy to remain as popular as they are, there has to be a continuing stream of exciting new results to present.

1. Television

Cosmos is the most successful public television series in history, seen by about 400 million people in 60 countries. The book version is the best-selling English-language science book ever, and the home video version had 100,000 orders placed for the full 13 episodes before release, an unprecedented number for any kind of videotape. Other astronomical television items include:

Project Universe, a series of 30 half-hour programs which reached its 100th showing in 1989, most broadcasts being on local stations in cooperation with nearby colleges offering credit for the series as a course.

Extensive, widely-watched coverage of the Voyager Neptune encounter, whose audiences included millions of young people in and out of school, and a large number of Pasadena residents and visitors (even some European amateur astronomers who flew in for the occasion), who watched in real time at an auditorium near the Jet Propulsion Laboratory (JPL).

A Galactic Odyssey (funded and produced by Japanese National Television) and The Astronomers' Universe (funded by the Keck Foundation and produced by KCET), which are 6-8 hour series focusing on astronomy and the people who do it, scheduled for 1990-91 broadcasts. One of the stated purposes of the Keck- sponsored series is to motivate pre-college students to consider careers in science and technology.

2. Astronomy in Print

Astronomy is one of the few sciences with its own (profit-making) book club. A volume featured by book clubs will sell in the range of 40,000 copies (e.g., Herbert Friedman's *Sun and Earth*), while one of the all-time winners, Stephen W. Hawking's *A Brief History of Time*, has reached the one-million mark and spent two years on the New York Times best seller list. The 1988 New York Times list of ten best non-fiction books included three on astronomy, and the subject is similarly over-represented among the winners of the American Institute of Physics science writing award.

Sales of magazines in 1988 reveal 632,500 regular readers of Scientific American, 95,000 of Sky and Telescope, and 165,000 of Astronomy, indicating that 20-25 percent of the audience for science at this level is specifically an audience for astronomy. Within the broader-based magazines (Discover, Science Digest, Scientific American, and Science 80-86) about 7 percent of the articles over the past decade have dealt with astronomy. In contrast, professional astronomical journals make up 0.5 percent of the 3300 covered by Science Citation Index, and astronomy Ph.D.'s make up about 0.7 percent of the 18,000 awarded each year in physical biological, social, health, engineering, and computer sciences (Kidd 1989).

While few papers cover astronomy as regularly as astrology, the subject is over-represented relative to other sciences in newspapers as well as magazines. For instance, 10 years of articles in the New York Times, Wall Street Journal, Washington Post, and LA Times include 325 items on astronomy and space sciences, 360 on physics, and 280 on biology (excluding medicine; J. Cornell, Center for Astrophysics, personal communication 1990).

3. Observatories, Planetariums, and Museums

Of the 9.4 million visitors to the National Air and Space Museum in 1988, 36.2 percent (based on random sampling of departing visitors) found the astronomy and space exhibits more interesting than the aviation ones. About a third of a million visitors saw the planetarium show. On smaller scales:

All but two of the fifty states have observatories or planetariums regularly open to the public.

McDonald, Palomar, and Kitt Peak Observatories report that about 100,000 people per year travel the relatively large distances necessary to visit each of them. McDonald Observatory has been featured in the monthly Texas hotel magazine for tourists.

Griffith Observatory, near Los Angeles, more accessible than the research observatories, hosted 1.7 million people in 1989, as many as the Los Angeles Museum of Art and the John Paul Getty Museum together (879,000 and 338,800 respectively). The Adler Planetarium in Chicago records about 700,000 visitors per year. The total number of planetariums in the U.S. is about 1000.

4. Radio and Telephone Hot Lines

Stardate–daily five-minute programs produced by the University of Texas–is carried (and paid for) by about 200 radio stations, including some large ones like KNX in Los Angeles and KCBS in San Francisco. It has received a Corporation for Public Broadcasting award for excellence and attracted half a million letters from listeners over the past decade. Its spin-offs include a Spanish-language version, one minute TV news spots, and part of a CD-ROM computer commercial demonstration disk.

At least 20 astronomical telephone hot lines operate in the US. Most change about weekly and feature a mix of local observing information (moon phases, planets, and so on) and research news. A typical one, Starwatch at University of Minnesota, receives about 30 calls a day (more during Voyager encounters, Halley perihelion, etc.) and portions of its content are carried by a dozen local newspapers. Incoming students at the University sometimes mention that Starwatch was a factor in their choosing the institution and a science major.

5. Amateur Astronomy

Every state in the union has at least one active astronomy club. More than 240 dealers and manufacturers are engaged in the business of providing telescopes, accessories, and software for observers who are not professional astronomers. Some highlight activities are the following:

Telescope and magazine sales suggest that roughly 200,000 people take some interest in amateur astronomy. Of these, more than 14,000 belong to the main umbrella groups, the Astronomical League and the Western Amateur Astronomers.

The Planetary Society, whose members contribute $25 per year toward the cause of exploration of the planets and the search for extra-terrestrial intelligence, has about 130,000 members. Their publication, The Planetary Report, recently reported results of a random survey by the Public Opinion Laboratory at Northern Illinois University indicating that half or more of adult Americans support the Society's goals.

The American Association of Variable Star Observers provides a bridge between the amateur and professional communities. Of its 1100 members, about half each year provide about 250,000 observations of 3500 stars to a central data depository. Amateur observers of variable stars thus outnumber the professionals (about 100 of whom per year make use of AAVSO data). The total number of contributors over the history of the society is nearly 5000, equal to the current membership of the AAS.

Another important AAVSO contribution is providing data to educators for astronomically-based labs and science projects. Association membership data indicate that amateur astronomy participation among young people serves to recruit both future astronomers and scientists, engineers, and programmers in other disciplines.

Amateur astronomers frequently share their interests and expertise with Scout troops, school classes, and other groups of young people.

B. Contributions to the Pool of Scientifically Trained Personnel

About 70 American colleges and Universities currently offer degrees in astronomy or closely related fields, awarding about 100 Ph.D.'s per year, 160 B.A.'s and B.S.'s, and 40 terminal M.A.'s. Most of the recipients who do not pursue long-term careers in astronomy do remain part of the manpower pool in science- and technology-intensive fields.

1. Ph.D. Recipients

As indicated in the report of the Panel on Status of the Profession, about half as many astronomers leave the field each year as receive new Ph.D. degrees. Complete samples of 106 doctoral recipients (1952-88) from the California Institute of Technology and 94 (166-88) from the University of Maryland confirm this. About half are primarily engaged in astronomical research; 20 percent are employed in other sciences and in industry; 7 percent hold teaching or science administration positions; and most of the rest work on hardware or software in support of astronomical or related research.

2. B.A./B.S. recipients

Of recent astronomy bachelors, a little more than half go directly on to graduate school (a third of them in astronomy) and the others enter the work force directly (Ellis and Mulvey 1988). Complete samples from a few institutions over a longer time period confirm this pattern. The samples include Swarthmore College (28 B.A.'s, 1940-85), California Inst. of Technology (140 B.S.'s 1956-88). and Williams College (26 B.A.'s 1974- 89). 35 percent are in astronomy (research, supporting activities, or graduate school); 39 percent are engaged in other sciences or are employed in technologically intensive industries; 11 percent are teaching; and 15 percent are in non-science occupations (including law, photography, writing, and many others).

Undergraduates in astronomy are much more likely than those in most other sciences to engage in significant, publishable research; and this may contribute to the high retention rate. If so, there might be a useful example to be followed by other sciences where the ratio of Ph.D.'s to B.A./B.S. degrees is much lower, averaging about 5 percent over all the natural sciences.

III. TECHNOLOGY TRANSFER, SPIN-OFFS, AND THE PRIVATE SECTOR

Astronomy has benefited from technological advances made in many fields in science and engineering, but astronomy also contributes to technological advances in two ways. First, the demands of researchers for devices at the very edge of what is possible have sometimes been the drivers for industrial development whose products were then useful elsewhere. Photographic emulsions are a classic example. Second, ideas, algorithms, devices, processes, materials, and so forth invented within the astronomical community are from time to time modified for use in other areas: the radio astronomy technique of aperture synthesis is such a case. The first four subsections categorize items by the fields in which they are applied rather than the part of astronomy within which they originated. The concluding subsections briefly address some potential areas for future technology transfer and the support of astronomy by the private sector.

A. Medicine

The single largest problem shared by medicine and astronomy is that of imaging things you cannot get to and of reconstructing two or three dimensional structures from a number of one or two dimensional scans. Astronomers, especially radio astronomers, led the way in solving this problem. Martin Ryle's Nobel Prize cited his development of aperture synthesis, and the solution to image reconstruction pioneered by Bracewell and Riddle (1967) is now used in CAT scanners, magnetic resonance imaging, positron emission tomography, and other medical imaging methods.

Specific computer languages and ways of handling large data arrays have also proven transferable from astronomy to medicine. IDL (Interactive Data Language) and IRAF (a very flexible image processing system) are products of optical astronomy. Their medical applications include

- Study of activity and chemistry of neutron in the brain (University of Southern California).
- Cardiac angiography and PET scans (University of Michigan).
- Magnetic resonance imaging (National Inst. of Health).
- Medical imaging and product development (Mallinkrodt Institute of Radiology and Siemens Gammasonics).
- X-ray computer tomography (PDA Engineering).

The need for clean environments is another problem common to medicine and astronomy. A version of the positive pressure clean room designed at the University of Wisconsin for work on the OAO- 1 satellite is now in many hospitals. NASA's needs for contamination-free environments led to data bases, handbooks, and courses for clean room personnel, as well as air handlers and "bunny suits" whose commercial versions appear in hospitals and pharmaceutical labs.

A U.S. drug company has teamed up with the Cambridge (U.K.) Automatic Plate Measuring facility to use its expertise in scanning and interpreting images to analyze blood samples from leukemia patients. This permits much more rapid detection of responses to changes in medication and other pharmacological effects than would otherwise be possible.

Radio astronomers have adapted their methods of measuring microwave temperature for non-invasive detection of tumors and other regions of vascular insufficiency. Microwaves have poorer angular resolution than infrared but are more sensitive to deep tissue temperatures. The combination of microwave and infrared thermographic data provides a true-positive detection rate of 96 percent, better than either alone, for breast cancer (Barrett *et al.* 1978)

Tiny paste-on thermal sensors first designed to keep ultraviolet detectors within their narrow operating temperature range have been adapted for controlling heat lamps in neonatology units.

Finally, the X-raying of people shares with X-ray astronomy the problem of having fewer photons than you would like to work with. Thus the Lixiscope (low intensity x-ray imaging scope), a portable, low-energy X-ray scanner to which NASA holds the patents, is widely used in neonatology, out-patient surgery, diagnosis of sports injuries, and third world clinics. The FDA even used it to search for poisoned capsules during the Tylenol scare a few years ago. A second generation spin-off, the Fluoroscan imaging system, has a variable power X-ray tube source among other improvements and a wider range of applications, including catheter placement.

B. Industry

The two kinds of spin-off (driving development and originating ideas) are illustrated by astronomical interactions with photography and the communications industry.

As early as 1912, C.E.K. Mees (the first research director at Eastman Kodak) initiated research leading to special series of spectroscopic plates to meet astronomical needs. The sensitizing dyes and emulsion-making techniques resulting from this work led to products of wide utility. One example is gold sensitization, which made possible Tri-X and a number of other 400-speed films from Kodak and other manufacturers. These have dominated the professional and amateur high speed film market for a number of years.

Kodak Technical Pan film, whose sharp resolution and fine grain permit enormous enlargements, is used by medical and industrial spectroscopists, industrial photographers, and serious fine-art photographers. It was first developed for solar astronomers interested in recording changes in fine scale surface structure.

Red and infrared-sensitive emulsions, evolved for spectroscopic plates, now penetrate military camouflage, and detect diseased crops and forests. Other applications include dentistry, medical diagnosis, and probing below the surface of paintings for evidence of forgery or pentimentos. Hypersensitization techniques, developed by astronomers during the 1970s, show promise in medical and industrial microscopy and in autoradiography.

Radio astronomy has been a copious source of transferable technology, algorithms, and people interested in applying them, especially in communications. Millitech, whose founders came from the University of Massachusetts radio astronomy group, now builds millimeter wavelength components based on devices used in radio astronomy, for the communications industry. Their products include varactor multipliers, voltage-tunable Gunn oscillators, and cooled GaAs Schottky mixers (Weinreb and Kerr 1983).

Radio astronomers also founded Interferometrics (Vienna, Virginia) which tests and evaluates antennas using holographic methods first reduced to practice by British radio astronomers. A holographic map of a dish surface takes a few hours (versus several days for a mechanical survey) to reveal high and low spots that must be corrected before (for instance) sidebands are low enough to meet FCC standards for satellite communication links.

High density recording techniques have come from both NRAO and Haystack Observatory. Digi Data of Maryland is marketing several versions of the NRAO version (which achieves 2.5 Gbyte capacity and 120 kbyte/sec data rate by storing digital data in analog form) for archiving of business data, disk backup, and other applications. The Haystack technique uses a 36 channel, high accuracy narrow-track headstack that can be moved precisely across tape to increase the density of the recorded information by a factor of more than 12, so that a single reel accommodates nearly 6 terabits and can record at a rate in excess of 1 Gbit/sec. Honeywell of Denver is now producing these high- density headstacks as a standard component.

Radio astronomers have been both drivers and developers of low noise amplifiers, including cryogenically-cooled gallium- arsenide field effect transistors (now marketed by Berkshire Technologies, also founded by radio astronomers) and high electron mobility transistors, which may replace masers in some communications amplifiers.

The computer control language FORTH was invented by a professional programmer with a strong interest in astronomy and first applied by him to coordinate telescope operation, data acquisition, and initial reduction for the NRAO 36-foot dish at Kitt Peak. It has grown into a profitable company (Forth, Inc., Manhattan Beach, California) and been modified for a wide range of purposes in manufacturing and service industries. About 20 vendors supply Forth systems for hardware from handheld computers to VAX mainframes. Some computers (most recently the Harris RTX 2000 microprocessor) execute Forth directly. The system is currently used in a rule based ("expert system") automobile engine analyzer at over 20,000 service stations world wide and in a high-accuracy densitometer used by Kodak for quality control in film manufacture. The initial support from NRAO and wide diffusion of Forth through the astronomical community were instrumental in its development into a broadly-applicable system.

Other examples of fruitful technology transfer from astronomy include:

- Use of AIPS (a set of image processing programs from radio astronomy) by Boeing to test computer hardware (several vendors, including Convex and International Imaging Systems advertise that their systems support AIPS).
- General Motors' application of IDL to analyzing data on car crashes.
- Acquisition of the patents for the first gravitational radiation detectors by Hughes Research Laboratory for use in modified form to sense gravity anomalies associated with underground oil pools.
- Use of the IRAF image processing program at AT&T for solid state physics graphics and computer systems analysis.
- Cold spot welding techniques that do not distort the underlying metal, developed at University of Wisconsin during construction of OAO-I.

C. Defense

The common technological needs of astronomical observations and of certain defense programs have often resulted in one research community developing techniques or making observations useful to the other. For example, satellite and aerial surveillance have replaced many ground-based intelligence activities. The resulting increased certainty (on both sides) that accurate information will be available has contributed to recent progress in arms reduction. Surveillance requires telescopes with large accurate mirrors, precision optics, and the ability to process numerous imperfect images and extract the maximum possible amount of information. The necessary large mirror technology, adaptive optics, and processing algorithms have all had significant input from techniques developed within astronomy and by people trained as astronomers, from the time of the U2 cameras to the present. Some specific examples which extend across the electromagnetic spectrum:

- A recent investigation at Grumman on recognizing rocket plumes for strategic warning purposes made use both of observations of stars and of model stellar atmospheres to discriminate plumes from cosmic objects.
- Aperture synthesis radar is the remote descendent of the radio astronomy technique for which Martin Ryle won the Nobel Prize.
- Development of the channeltron was supported originally for ultraviolet astronomy, but it has since found its way into various uv military cameras.
- Expertise developed in conjunction with the Kuiper Airborne Observatory has provided direct support to several Navy and Air Force airborne infrared sensor development programs.
- Star counts and models of stellar spatial distribution are used to assess data rates for spaceborne signal processors and sensors as well as for satellite pointing and calibration.

- Astronomers who had been working on X- and gamma-ray detectors at Los Alamos helped build the instruments for the Vela satellite monitors.
- Solar blind photon counters were invented for uv astronomy and later adapted to sensing the uv corona round supersonic objects in daylight and for toxic gas detection.
- The Air Force Weapons Laboratory at Albuquerque has issued a number of contracts to astronomers to investigate topics like optical imaging of satellites in geosynchronous orbits using 10-30 meter baseline optical interferometry.
- The infrared maps of the sky obtained by IRAS met DoD needs for information that the Air Force Geophysics Lab rocket program had been unable to provide.
- The techniques being developed by Itek, LBL, and others for stress polishing of off-axis mirror segments for the Keck telescope have potential defense uses.

The early development of thermonuclear weapons made extensive use of astrophysical knowledge of radiative transfer and temperature/density diagnostics. At the present time, 69 American Astronomical Society (AAS) members are employed at Los Alamos and Sandia National Laboratories and another 32 at Lawrence Livermore National Laboratory, most of them at least partly on programmatic work. A background in astrophysics appears to provide flexibility and skills in carrying out approximate calculations based on integrating information from a variety of sources that are a good match to defense laboratory needs.

The presence of Soviet reactors in space has apparently been known to DoD for some time, but astronomical gamma-ray detectors on the Solar Maximum Mission and on a University of California, Riverside balloon-borne experiment made independent discoveries of the phenomenon (Rieger *et al.* 1989; O'Neill *et al.* 1989).

Looking ahead, the Navy is supporting neutrino astronomy for its long-term potential for communicating through the earth and for long distances under water. Solving the engineering problems associated with DUMAND (Deep Underwater Muon And Neutrino Detector) should lead to valuable new oceanographic technology as well. Grazing-incidence X-ray optical devices, which have been reduced to practice for solar astronomy, are likely to find future applications in laser weapons.

Another area where astronomical and defense interests overlap is in the need for precise coordinate systems, times, and time intervals, for use in navigation, clock synchronization, guidance, and secure communications as well as in astrophysics. The fundamental time standards are now atomic clocks, not the earth's rotation, but the determination and dissemination of time data for the U.S. are still the responsibility of the U.S. Naval Observatory (USNO). Accurate measurements of the earth's rotation rate are needed to keep civil time in step with astronomical time. This must be done for navigational and other purposes and is accomplished by a network of radio and optical observing stations, maintained by USNO and observatories of many other nations. Very Long Baseline Interferometry between widely separated radio telescopes was the original driver to turn hydrogen maser clocks into rugged, off-the-shelf items, whose main users are now space communications and DoD. In addition, VLBI methods are currently used to synchronize widely separated clocks at the nanosecond level.

The fundamental celestial coordinate system used for navigation is now a radio based one. The locations of the artificial satellites which make up the Global Positioning System and which transmit their own radio signals are in the process of being tied to the positions of quasars and other distant sources. Inertial guidance systems (for missiles and other purposes) require this accurate astronomical coordinate system for their calibration. Accurate optical star positions are used in surveying and in automated star-tracker guidance systems. The tying together of accurate radio and optical coordinate systems is a topic of current intense study. Finally, because satellite orbits are blind to the assorted wobbles of the earth beneath, correct location of terrestrial targets (for environmental and surveillance imaging as well as bombing) requires accurate forecasts of earth orientation. USNO is also responsible for providing and disseminating this information, which comes largely from VLBI observations of quasars, in the U.S.

D. Energy and the Environment

The search for fossil fuels and alternative energy sources has benefited from astronomical spin-offs in several contexts. For instance,

- Texaco, Inc. and BP America both use the image processing program IDL for analysis of drilling core samples and other aspects of petroleum research.
- SAIC (San Diego) has built solar radiation collectors up to 16 meters in diameter using graphite composite materials first developed in design studies for a proposed orbiting telescope called the LDR (Large Deployable Array).
- Grazing incidence X-ray optics was reduced to practice for solar astronomy and now finds application in plasma diagnostics for magnetically confined plasma fusion. Detailed knowledge of atomic spectra at high temperatures, gained from study of the solar corona, is also important in this context.
- Plasma and magneto-hydrodynamic phenomena, including magnetic reconnection and radiation-driven thermal instabilities, were first explored in solar and space physics environments. They also occur in fusion plasmas (and are deleterious there).

Remote sensing from orbiting satellites is now the method of choice for keeping track of an enormous range of ecologically important factors–the extent of the Arctic ice pack; the moisture content of soil in the Sahel; upper atmosphere profiles of temperature, density, and trace constituents; sea surface temperatures; and many others. Astronomically-derived image processing algorithms are widely used in these applications. Several of these are mentioned elsewhere. Another with many remote sensing and oceanographic uses is a digital correlation technique for spectral analysis of broadband signals which came out of radio astronomy (Weinreb 1963; Cooper 1976)

Specific radio, microwave, and infrared spectroscopic methods from astronomy have also proven useful in environmental applications from space and ground. Downward looking millimeter wave sounding traces back to work on the atmospheres of Venus and Mars and was validated for the earth by radio astronomers using balloon borne telescopes. The technique is operational on the current Defense Meteorological Satellite Program (DMSP) and will be the primary temperature sensor on the next generation of NOAA satellites in the 1990s.

Millimeter wave technology in space (e.g., Staelin 1981) is sensitive to composition as well as temperature of the atmosphere, including greenhouse gases in low concentrations. Microwave sounders, scheduled for the ATLAS series of spacelab experiments and for the Earth Observation Satellites, were developed by a consortium of American and European radio astronomers and atmospheric scientists.

A particularly timely application of microwave astronomy techniques from the ground is study of chlorine chemistry (relevant to ozone depletion) in the Antarctic. In September 1986, instruments developed by radio astronomers at SUNY, Stony Brook found a hundred times the normal concentration of chlorine oxide at an altitude of 15-20 km in the Antarctic ozone hole. The excess disappeared in October, verifying the role of manmade chlorine compounds in ozone depletion. The detailed chemistry had earlier been tested by the group's measurements of the diurnal variation of chlorine oxide in the middle stratosphere above Mauna Kea. The Antarctic spring cycle of chlorine oxide rise and fall was followed through the 1987 season with better instrumentation yielding the full concentration profile from 16 to 40 km. Monitoring at about five sites around the world over the next 10-20 years is planned as part of the NASA-sponsored Network for the Detection of Stratospheric Change.

E. Everyday Life

Many of us benefit regularly from the machinery used to X-ray luggage in airports, whose design descends from that of the earth rocket and satellite borne X-ray telescopes. Airport surveillance for drugs and explosives makes use of a particular gas chromatograph design supported by NASA for use on Mars. Some other mundane spin-offs from ground and space-based astronomy include:

- A hand-held COD photometer developed by astronomers at University of Hawaii for use by policemen checking the transparency of automobile windshields
- A non-invasive probe for contaminants likely to cause structural weakening in historic buildings; it has a neutron source and gamma-ray spectrometer, was first used to analyze lunar soil, and has been tried by astronomers at GSFC in a Colonial Williamsburg smoke house and at St. Mark's Basilica in Venice to look inside the walls behind fragile mosaics.
- Software to process two-dimensional images on a personal computer, developed by Michael Norman at the National Center for Supercomputing (Illinois) for his own astronomical purposes and modified for public consumption; about 10,000 copies have been sold.

- Use of Forth in the hand-held computers carried by the 40,000 delivery agents of one of the major express mail firms.
- Application to industrial and amateur photography of enhancement techniques developed by David Malin for handling astronomical images from large telescopes (Malin 1982, 1990).

F. Looking Ahead

Technology transfer is an ongoing process. For instance, observers are currently driving COD technology (as they did photography earlier) in the direction of thinning the chips to broaden the range of wavelengths over which they are sensitive. And astronomers are pushing for cryogenic infrared array detectors with very low backgrounds and long integration times, so that they can be used at low light levels. These technologies are likely to prove useful for non-astronomical purposes.

X-ray astronomers have been responsible for the development of bolometers and superconducting devices as non-dispersive spectrometers. The entire energy of the of the absorbed X-ray is transformed into an electrical signal via phonons, producing a much larger response for a given X-ray energy than in photoelectric detectors. These have potential applications in non-destructive testing and in medicine, where getting the largest possible signal out of the fewest possible X-rays is also important.

Many radio astronomy observatories with millimeter-wave antennas are currently developing SIS (superconducting- insulating-superconducting) mixers for low noise receivers. NRAO is among these and has begun technology exchange with several commercial and government organizations (Hypress, NRL, the National Security Agency, etc.) who are interested in non-astronomical applications. Millimeter- wave astronomers are also working on error- correcting secondary mirrors and lenses. Such error-correcting optics is likely to be part of high-performance communication, surveillance, and other non-astronomical antennas and telescopes of the future.

G. Astronomy and the Private Sector

No other branch of science, except medicine, has had as much support as astronomy from private individuals, industrial firms, and foundations. Two of our great observatories, Lick and McDonald, bear the names of the men whose bequests founded them. Both are now largely maintained by state and local, not federal, funding. Contributions from Rockefeller and Carnegie and the foundations they established have built and helped maintain the Yerkes, Mt. Palomar, Mt. Wilson, and Las Companas Observatories. More recently, Oscar Meyer provided some much-needed new buildings for Palomar. And money from the Keck Foundation is even now being transformed into a ten-meter telescope that will be the largest American optical observing facility for the next generation.

The motive for this generosity (apart from tax laws) appears to have been the breadth of vision needed to span a nation with railroads or to build up a steel industry appreciating the breadth of vision needed to span the Universe and build an understanding of it. Other interactions have been of more obvious mutual benefit. Kodak has donated the several thousand 14"x14" photographic plates needed for the second Palomar Observatory Sky Survey because this use with long exposure times and low light levels provides a critical test of their emulsions. A recent document from the American Institute of Aeronautics and Astronautics (1989) encourages federal support of the Hubble Space Telescope and similar projects because "such cutting edge technology programs stimulate commercial spin-offs of potentially great value to industry and to the nation's economy."

The process of compiling this report revealed that people whose livelihoods in no way depend upon astronomy can nevertheless feel that it is an essential activity. Whenever the AASC received a bit of publicity, they wrote, phoned, and sent photocopies emphasizing that astronomy is needed to attract students into science and technology, to inspire long-range advances (e.g., neutrino communication), and to form part of the human intellectual adventure–much the same points the Panel has identified.

IV. MAN'S PLACE IN THE UNIVERSE

As far back as history records, peoples have attempted to understand how the world got to be the way it is, what the big picture is, and how we fit into it. Anthropologists call the answers (even answers they believe) creation myths. Our modern Western myths have a long history, with input from Greek philosophy, from Judeo-Christian religious ideas, and, at several critical points, from astronomical research.

The Copernican revolution was the most obvious and far reaching of these. The earth ceased to be the unique center of everything and declined to merely one of several planets orbiting the sun. With further celestial study, our sun, in turn, metamorphosed into a typical, undistinguished star, not even at the center of the Galaxy. A third of the way into the 20th century, our Milky Way Galaxy itself had shrunk to a status neither special nor central to anything. In fact, cosmic models incorporating general relativity show that all places in the Universe are equivalent, there being neither any center nor any edges. And in just the last few years, a picture of the very early Universe motivated by theory on the frontier between cosmology and particle physics has made it seem plausible that the Universe–the entire four-dimensional space-time with which we might ever communicate–is only one of many universes, dictionary definitions notwithstanding.

Curiously, other recent astronomical research has pushed our thinking back a little bit in the other direction. The life- bearing earth really is very different from the other nearby planets. Looking down at it from space, we can see our home as a single, small, fragile entity, whose residents all have a common, profound interest in its well being.

Other 19th and 20th century discoveries clarify other aspects of our relationship to the rest of the Universe. The spectra of the sun and stars show absorption and emission lines in just the same patterns that are radiated by common chemical elements when you heat them in the laboratory. Thus celestial objects do not consist of some "quintessence" or substance unique to them. They are made of the same stuff that we are, and even in more or less the same proportions. Apart from helium (which forms no stable compounds), the commonest elements in the stars are the hydrogen, oxygen, and carbon that make up most of our bodies. Close study of spectra of distant galaxies and quasars reveals not only this commonalty of composition but also that the constants and laws of physics are the same at distant times and places as they are here and now on earth.

The totality of modern astronomy makes up a major part of our Western creation myth, answering many of the traditional questions about how big, how old, and what came before. The world, or Universe, is large. It is the same in all directions (on large enough scales). It expands and is only three or four times older than the earth itself (but the earth is some 100 million times older than the span of an average human life). We are made of starstuff–chemical elements built up from hydrogen atoms by nuclear reactions in massive stars. And chemical reactions in interstellar gas and in the material that formed the meteorites and comets have produced the same molecules that are the building blocks of living creatures on earth.

The task of clarifying our relationship to the rest of the Universe is an on-going one, with many important questions still incompletely answered. It is, for instance, just becoming meaningful to ask whether the Universe could have been very different from what it is (in size, age, laws of physics, kinds of particles, and so forth) and whether such a different Universe could have life arise in it. On smaller scales, detailed studies of Mars and Venus will play an important part in understanding the early evolution of the earth's atmosphere, oceans, and biosphere, and in determining just how delicate the present state of terrestrial habitability is likely to be.

The "where do we belong" aspect of astronomy seems to be responsible for most of the popular interest in the subject. The potential for technology transfer and for attracting students into the sciences may be good (though not central) reasons for funding astronomical research. But they are not the reasons that people watch Cosmos, buy and build small telescopes, or read books and articles about astronomy. Rather, these people are seeking new answers to the old human questions about the world and our place in it.

An important property of the modern creation myth is that its answers are neither static nor given by fiat. Everything (or nearly everything) within the sciences is subject to change without notice. Our picture of the Universe expands and evolves as our knowledge expands and evolves. A vigorous continuation of this process can help to keep human minds flexible enough to deal with immediate practical problems that now also change on timescales much less than a human lifespan. Practicing astronomers feel a great deal of certainty that, although any given piece of information may turn out to be wrong, the basic process of inquiry is sound and leads to continuously better understanding of the world around us. Confidence that the Universe is neither incomprehensible nor intrinsically hostile is perhaps the most important return astronomers can offer to their fellow citizens.

Astronomy as part of our world view has a less serious side as well. For instance, the phrase "black hole" seems to have entered the everyday vocabularies of Rep. Bill Frenzel (R-Minn.), New York Yankee Don Mattingly, and Supreme Court Justice Sandra Day O'Connor in various contexts (Montgomery Journal, April 26, 1990, p.2). "Astronomical" distances and amounts of money and "zeniths" and "nadirs" of achievement and despair are also common phrases.

Modern astrophysics has not inspired any artistic works comparable with Dante's treatment of medieval cosmology's circles of heaven and hell, but Van Gogh's "Starry Night" reveals a mind not unmoved by the Universe as it is now understood. And each new astronomical–discovery novae, supernovae, neutron stars, black holes, multiple Universes, and many others–has inspired science fiction films, stories, and novels tying these discoveries to possible individual lives.

V. INTERNATIONAL COMPETITION AND COOPERATION IN ASTRONOMY

Science and technology are normally perceived as factors in international competition, both military and economic. That aspect is by no means absent in astronomy. Most of us are really rather proud of the long list of American "firsts" and "bests" (the Apollo Program and Viking Landers; large optical telescopes; Uhuru and COBE; the VLA and the VLBA; and so forth) and pleased by the leading role that the U.S. has played in the International Ultraviolet Explorer (IUE), the Infrared Astronomy Satellite (IRAS), the Hubble Space Telescope, and the establishment of intercontinental networks of VLBI stations.

We believe that it is important for the U.S. to continue to take, and be seen to take, a position of leadership in astronomy, astrophysics, and space exploration. Benefits of remaining at the forefront in research include a strong positive image in the eyes of the nations we interact with, the potential for future spin-offs, and opportunities for fruitful international collaborations. The ability of the U.S. to continue to attract outstanding students and young researchers from abroad is also vital for the continued health of science and engineering here. About one-quarter of the astronomical research community in both senior and entry-level positions is foreign born (Trimble 1988). Among graduate students in engineering and physics, the proportion is roughly one half. Because the results of astronomical research receive a good deal of media attention, leadership in this field can contribute disproportionately to a positive American image abroad.

The world is, however, entering an era in which international cooperation will replace competition, at least so we all devoutly hope and possibly even rationally expect. Among the sciences, astronomy has an unusually long and rich history of internationalism dating back to before the 19th century. One important driver for collaborations is the absolute necessity of observatories spaced over the surface of the earth necessary to see the whole sky. In addition, the perceived impracticality of astrophysical research has probably helped it to be seen as a safe area for contact when there were not many others. Beginning in 1887, two American observatories were among the 18 world wide that banded together to produce a map of the entire sky (Carte du Ciel). The International Astronomical Union was the first of the modern international scientific unions organized, in 1920, under the Treaty of Versailles, with the U.S. as one of the founders.

A large fraction of new observing facilities, spacecraft, and research programs are international collaborations. The European Southern Observatory and the Canada-France-Hawaii telescope are self- explanatory. The latter peacefully shares the top of Mauna Kea with a British infrared telescope and several American projects. Construction of a Japanese observatory there is expected to begin in the next decade. Other recent success stories include the following:

- The sharing of the International Ultraviolet Explorer observing time between the European Space Agency and NASA (in ratio 1:2) over the past 13 years.
- An American (University of California–Berkeley) spectrometer launched by a Japanese rocket to study the cosmic microwave background.
- European-built instruments on IRAS and HST, with proportionate sharing of the observing time.
- An American instrument on the Soviet Vega 1 and 2 spacecraft that flew past comet Halley. Soviet scientists participated in the Voyager 2 encounter with Neptune.
- The 20 percent of the papers published in the Astrophysical Journal in 1990 that had authors headquartered in the US and at least one other country (Abt 1990).

Scientists and administrators in the United States and the Soviet Union have even begun exploring the idea that the first manned mission to Mars should be a joint one.

On a more personal level, most American astrophysicists count at least a few foreign colleagues, often including some from ideologically very diverse countries, among their closest friends, though they may not meet more often than the triennial General Assemblies of the International Astronomical Union. Perhaps contemplating very large scale phenomena makes small scale differences a little easier to overlook. Because astronomy and the defense industry already share some hardware, techniques, and personnel, gradual conversion of additional resources from competition in the latter to cooperation in the former may not be an unrealistic goal.

VI. SYNERGISM WITH OTHER SCIENCES

A. Historical Examples

Back when science was called natural philosophy, its practitioners were supposed to know a good deal about all of it. Thus it is no surprise that observations of planetary motions played a central role, through Newton's work, both in the elucidation of the properties of gravitation and mechanics and in the formulation of the calculus. Astronomy and mathematics continued to be closely linked into the 19th century. Gauss, for instance, invented the least squares method while struggling to describe discordant observations of the first asteroid (Ceres, found in 1801) by a single best orbit. This led to his subsequent investigation of the normal error distribution, crucial to a variety of statistical studies.

Later in the 19th century, astronomy came to be more closely linked to chemistry, through spectroscopy. Helium, the second most abundant element, first revealed itself as the source of an emission line in the solar spectrum recorded by Janssen at the eclipse of 1868. Later on, lines from high ionization and excitation states of elements like europium were often seen in stars before they had been studied in the lab.

In the 20th century, the closest links have been with physics. Cosmic rays were the main source of very high energy particles until about 1950, and the positron, muon, and pi meson were first discovered among cosmic ray secondaries. Eddington, contemplating the problem of stellar longevity in the 1920s, was the first to appreciate nuclear fusion as a potential source of enormous quantities of energy. The correct reaction chains describing these stellar processes were identified in 1939, just before nuclear physics disappeared into weapons laboratories all over the world. Hans Bethe and others who made fundamental contributions toward nuclear and thermonuclear weapon theory had cut their scientific teeth on the stellar problem.

In our own time, science has expanded far beyond any one person's powers of comprehension, and most scientists are, at best, intelligent laymen anywhere outside their own subdisciplines. Surprisingly, fruitful interactions continue to occur among sciences, often to the pleased surprise of those involved when they recognize, for instance, that statistical techniques invented to describe the survival of medical patients can be useful in interpreting the celestial X-ray background. The following sections present cases where astronomical data, concepts, and methods have been applied in other branches of science, including physics, chemistry, and earth and environmental sciences.

Many of these symbioses occur because the Universe is a laboratory far grander than any we can build. It accelerates particles to energies beyond those projected for the Superconducting Supercollider (though unfortunately not very many in any one place at the present time). Cosmic objects demonstrate the effects of stronger magnetic fields, emptier vacuums, and louder sonic booms (shock waves) that are beyond the reach of terrestrial phenomena. Thus a critical test of our understanding of a local phenomenon is sometimes whether the same model works when applied to the more extreme astronomical case.

B. Nuclear and Particle Physics

In recent years, astrophysics has pushed experimental and theoretical nuclear physics to their limits. Modeling nucleosynthesis, supernovae, neutron stars and the rest requires (1) masses, lifetimes, and cross-sections for highly unstable nuclei, (2) the equation of state of very dense matter at both zero and finite temperatures (up to densities where pions, hyperons, or strange matter may replace neutrons as the dominant particles), (3) cross-sections for common reactions that, for example, convert carbon into oxygen at such low energies that the laboratory reaction rate defies measurement, and (4) the lifetime of the neutron to unprecedented accuracy.

Topics in particle physics to which astrophysics has recently made contributions include the number of groups of fundamental particles that exist, properties of the neutrino, and the existence and nature of dark matter. Laboratory experiments between 1950 and 1980 had gradually demonstrated the existence of three groups of particles (associated with electrons, muons, and tau leptons) and seemed likely to continue to reveal additional groups. But the calculated abundance of helium produced in the early Universe (in comparison with the amount observed in relatively unprocessed astrophysical plasmas) was only marginally consistent with even a fourth group and clearly ruled out a fifth (Steigman 1989). Measurements from terrestrial particle accelerators (Abrams *et al.* 1989) now strongly suggest that there are only three groups.

A table of neutrino properties consists largely of upper limits. The tightest limits on charge and magnetic moment now come from analysis of the neutrino burst from supernova 1987A. The supernova limits on electron neutrino rest mass and on oscillations among neutrino types are comparable with the laboratory limits but are likely to be easier to improve.

Non-luminous material–dark matter–makes up 90 percent or more of the gravitating mass of the Universe as revealed by rotation of individual galaxies and motions of galaxies within clusters. The fraction rises to 99 percent if the Universe has, as many physicists suspect, precisely the critical density that separates ever- expanding from recontracting future dynamics. Particle physics beyond the standard model has provided a wealth of potential candidates for dark matter in the form of weakly interacting massive particles, topological defects, and many other strange entities.

None of the candidates has yet been unequivocally seen in the lab (though searches are underway) and the best constraints on their properties come from a variety of astrophysical processes: (a) they must not disturb energy transport in stars or the magnetic fields of pulsars and galaxies; (b) they must not distort nuclear reactions in the early Universe so as to produce the wrong proportions of hydrogen, helium, and lithium; (c) they must not have interfered with neutrinos and light from SN 1987A reaching us a few hours apart and in the expected strength; (d) they must not produce more gravitational lensing or more gravitational radiation than observations of quasars and pulsars tell us can exist; and (e) their behavior during the epoch of galaxy formation must promote, or at least not prevent, the formation of the structures we see.

This is currently a very rapidly evolving topic with many controversies, but if the dominant constituent in the Universe is not ordinary baryonic material (protons, neutrons, and the atoms made from them), then the astronomical observations probably have at least as good a chance as the laboratory tests of telling us what the stuff is.

The solar neutrino problem, on the other hand, has been with us in nearly its present form for twenty years. The three-fold deficiency of observed solar electron neutrinos compared to the best theoretical predictions may turn out to have been the first hint we had of fundamental new physics linking the three particle groups of the standard model. The right answer could also turn out to be some even more exotic new physics not yet thought of, or some fairly uninteresting erroneous detail in stellar structure modeling.

C. Physics of Fluids and Plasmas

Astronomical objects present a much wider range of scales and properties than can be achieved in the laboratory. Pulsar magnetic fields are a million times stronger, solar convection Reynolds numbers a million times larger, and intergalactic vacuums more than a million times emptier than the most extreme terrestrial conditions. But the underlying physics is the same. Hence astronomical phenomena can provide valuable constraints on our understanding of terrestrial physics, for instance,

- Pulsar radiation mechanisms for microwave generating devices
- Solar flares for magnetic reconnection in Tokomak plasmas
- Astronomical cooling functions, Stark coefficients, and oscillator strengths for controlled and uncontrolled thermonuclear fusion studies.
- Instabilities in quasar jets for confinement of laboratory plasmas.

Some theoretical methods have also proven transferable. Smoothed particle hydrodynamics, now the most widely used method of modeling complex three dimensional fluid flows, was developed by a Columbia University astrophysicist studying binary stars.

D. Chemistry, Spectroscopy, and Atomic Physics

The first comprehensive table of spectral lines reveals its origins in its title, A Table of Multiplets of Astrophysical Interest (by Charlotte E. Moore) and its initial publication as Contribution No. 20 of the Princeton University Observatory. The current edition retains the astrophysical title, but is used in industrial analytic spectroscopy and a variety of other non- astronomical contexts. The standard table of ultraviolet lines (Kelley 1987) similarly incorporates astrophysical data.

Microwave and infrared observations of astronomical objects have revealed molecules not previously known on earth, including HC_nN (with n up to at least 11), C_3H_2 (whose structure was inferred from the astronomical data, permitting later laboratory study), and HCO^+ in interstellar gas; C_3NH_2, and H_20^+ in comets; and SiC and SiC_2 in stellar shells. Some of these are actually not possible in lab settings, where densities are always high enough for frequent collisions. HCO^+ was the first molecular ion identified anywhere. Study of these is now a large, productive branch of chemistry.

Meteorites also contain some familiar substances, including tiny grains of diamond and silicon carbide. These cannot have been made by the high pressure processes operating in Kimberlite deep underground. They must have arisen from something analogous to vapor deposition. This is now being studied by industrial materials scientists in hopes of greatly reducing production costs of these useful substances.

On the theoretical front, the attempt to explain intensities of spectral lines from interstellar molecules first made clear the need to consider departures from thermal equilibrium and the populations of individual energy levels when calculating reaction rates. And the process of dielectronic recombination, now known to be important in setting the ionization structure in Tokomak plasmas, was first recognized as occurring in the solar corona.

E. Geophysics

Very Long Baseline Interferometry, as well as establishing precise coordinates of the radio sources observed, tells you the distances between the antenna pairs with a precision of about a centimeter for baselines up to several thousand kilometers. These are of geophysical interest where baselines span tectonic plate boundaries and known faults. Measurements across boundaries have confirmed that continental plates are currently moving at the average rates implied for the past few million years by seafloor data (typically 1-5 cm/yr).

Of more immediate importance to society are the measurements around active fault zones. These confirm slippage and deformation along the San Andreas and other active faults, again typically a few cm/yr when and where plate motion is occurring smoothly, and little or no motion when it is not. The resulting built-up stresses are released as earthquakes. For instance, measurements made before and after the November 1989 Loma Prieta quake showed that about 5 cm slippage had occurred during the quake in the Santa Cruz area, but very little around San Francisco, where there had been smooth motion at about 5 cm/yr before the quake.

Post-quake measurements at Loma Prieta and after two large events in the Gulf of Alaska show that significant sudden displacements occur as far as 40-200 km from the epicenters. These measurements are crucial to understanding the nature of the energy release in earthquakes, which in turn may provide clues that will allow us to predict them.

F. Environmental Sciences

If one or more of the major episodes of extinction of terrestrial species resulted from asteroids or comets hitting the earth, this is surely the most spectacular of the synergisms. Astronomical aspects of testing this model for the extinction of the dinosaurs (etc.) include (1) inventorying the numbers and orbits of potentially earth-impacting asteroids, (2) comparing the history of impact cratering on the earth with that on other planets, and (3) looking for things that might cause sudden drastic changes in orbits of objects in the outer solar system and thereby increase the numbers of earth-crossing comets and asteroids. A distant companion star and periodic crossings of the galactic plane have both been suggested.

The hypothetical phenomenon called nuclear winter (Turco *et al.* 1983) is closely related to this interpretation of extinction episodes in the Earth's past. The idea is that all-out nuclear war would place so much dust and smoke in the earth's atmosphere that the resultant cooling and inhibition of photosynthesis might actually be the most serious effects of the nuclear explosions. The best way of deciding whether extensive nuclear explosions will cool the earth, heat it, or do something entirely different is undoubtedly through modeling, tested by its ability to explain the historical record on earth and the other terrestrial planets.

Another vital area of interaction is solar-terrestrial relations. Two rather different kinds of phenomena are involved. First are well-established, short-term effects (mostly unpleasant) of sudden increases in the ultraviolet, x-ray, and particle radiation coming from the sun. The primary goal here is to understand how and why these increases occur well enough to predict them. Second are tantalizing hints of longer-term, more subtle effects on terrestrial weather and climate associated with small changes in the visible light output of the sun and other solar cycle effects.

On the short term, the 11 year cycle of solar activity (spots, flares, and other surface manifestations of changing interior magnetic fields) is just now coming down from a peak as high as any reached in the past 300 years. 1989 saw three flares of strengths that generally happen only about once a decade. The high energy radiation from such flares hits the earth's upper atmosphere, heating and ionizing it, and also modifying terrestrial electric and magnetic field structures right down to the ground.

Documented effects of the 1989 March and September flares include (1) a nine-hour power outage affecting six million customers in Quebec, Canada, resulting from currents induced in power lines and transmitters by the magnetic changes, (2) a billowing up of the heated atmosphere high enough that drag on assorted satellites and space debris changed so many orbits that the Air Force tracking system responsible for them suffered an overload, (3) changes in atmospheric ionization that disrupted radio communication at most frequencies, and caused a U.S. military alert when over-the-horizon radar was lost, (4) deviations of magnetic compasses of up to 10x from normal magnetic north, and (5) an increase in the amount of energetic radiation reaching aircraft altitudes to the point where a Concorde pilot would have exceeded his yearly permitted dose in 35 hours of flying; women in weeks 8-15 of pregnancy may also exceed radiation guidelines when flying under peak flare conditions (New York Times, Wednesday, 14 February 1990). Even short term warning of flare activity are useful against some of these effects.

Adverse effects of solar activity are likely to become more serious as power grids become more extended; satellites become increasingly vital for communication, navigation, and weather forecasting; and humans venture further outside the earth's protective atmosphere and magnetosphere. Clearly the main astronomical problem to be solved is that of accurate predictions of solar events. Already, seeing the beginning of a flare through optical monitoring permits a few hours' warning of the main particle impact, allowing astronauts and power companies to hunker down. Over days to weeks, we can forecast at least the likelihood of terrestrially significant activity, because active areas on the solar surface live for several solar rotation periods and will point at us once per period. Prediction through and between 11 year cycles requires a level of understanding we do not yet begin to have. A promising avenue for acquiring it seems to be a comparative study of the sun with the many other stars known to have 5-20 year cycles, correlating the patterns of activity to rotation periods, magnetic field strengths, and atmospheric structures of the stars. Astronomers are actively working on this.

On longer time scales. there are tantalizing hints of sun- driven climate changes. Measurements during the most recent solar cycles (for instance from the Solar Maximum Mission satellite) show that the total brightness of the sun changes about 0.1 percent between maximum and minimum activity. Most models say that this should cause a global temperature change of about 0.1 $^{\circ}$ C. It may or may not be significant (1) that the integrated solar activity, smoothed over several cycles, has increased roughly in phase with an apparent 100-year warming trend, and (2) that the Little Ice Age in the 1600s coincided with a time of exceptionally low solar activity. In addition to temperature changes cause by solar brightness changes, the climate might, in principle, be responding to changes in solar ultraviolet production of ozone, to stratospheric heating and ionization by solar energetic particles and radiation, and to extra-solar cosmic rays, whose penetration to the earth varies inversely with solar activity. We need to know more about both activity cycles and associated changes in solar brightness to decide how important these effects are. Again, detailed comparison of the sun with other cyclicly active stars is a promising line of attack.

G. Looking Ahead

Man-made changes in the earth's atmosphere may be coming perilously close to turning some aspects of solar-terrestrial relations into an experimental subject. Fortunately, nature has provided informative laboratories for studying the results of higher and lower solar illumination in the forms of Venus and Mars.

Some of the models now used at Goddard Institute for Space Studies to study large scale weather patterns on earth had their roots in work by James Hansen on the atmosphere of Venus. That planet, owing to its high albedo, actually absorbs less solar energy per unit area now than does the earth. Its high temperature is, therefore, due entirely to greenhouse warming.

The "runaway greenhouse" and "runaway ice age" characteristics of Venus and Mars set limits to the tolerance levels for habitable planets. The implications of current studies is that these tolerances are rather narrow–if not in comparison with the changes we are likely to induce on the earth soon, at any rate in comparison with the effects of the brightening of the sun that will occur over the next few billion years.

Astronomy will soon be in a position to provide auxiliary evidence of global warming, whether naturally or artificially induced, if it occurs. The ability to measure vertical motions and height changes of VLBI sites is still improving. These vertical measurements can be used to studying small changes in sea level which occur with warming (due both to melting of ice and to expansion of warming sea water). Sea level changes as small as a few millimeters are of interest and will soon be measurable.

Despite the slightly pessimistic implications of Mars and Venus, astronomers have been in the vanguard urging serious searches for life elsewhere in the Universe and attempts to communicate with it. Only too clearly, no one knows for sure how to do this or even whether there is anything to look for. But the most promising methods so far devised for SETI (Search for Extra-Terrestrial Intelligence) use the telescopes, receivers, amplifiers, and correlators of radio astronomy. The discovery of life elsewhere in the Universe could well be the most exciting scientific event of the millennium in which it occurs; and it has a good chance of being an astronomical discovery.

VII. ACKNOWLEDGEMENTS

The following colleagues, who are not members of the panel, have generously shared their ideas and expertise with us: Thomas F. Adams, Laura P. Bautz, Roger Bell, Gregory Benford, Leo Blitz, Matt Bobrowsky, Ralph Bohlin, Phil Bowers, Peter Boyce, Robert A. Brown, Robert Brownlee, Claude Canizares, Stirling Colgate, Edward K. Conklin, James Cornell, Tim Cornwell, Art Cox, Carol Crannell, David Cudaback, Grace Deming, Helene Dickel, Ann Druyan, Harland Epps, Eric Feigelson, Paul Feldman, John Gaustad, Mark Gordon, Martin Harwit, Robert C. Haymes, David Helfand, Ernest Hildner, James Houck, John Huchra, William Irvine, Tom Jones, Judith Karpen, Ken Kellermann, Jerry Krassner, Ed Krupp, Harold P. Larson, Barry Lasker, John Leibacher, Frank Low, Craig MacKay, John Mathis, Lucy McFadden, Christopher McKee, Adrian Melott, Michael Molnar, John Mulchaey, Richard Muller, Robert Noyes, R. Bruce Partridge, Jay Pasachoff, Peter Pesch, David Pierce, Caty Pilachowski, William Press, Ralph Pudritz, Kumar Ranohalli, John Rather, Steve Ridgway, Larry Rudnick, Joseph E. Salah, Blair Savage, David Schramm, Philip R. Schwartz, James S. Schweizer, Frederick Seward, David Shaffer, Steven Shore, Alex G. Smith, Peter L. Smith, Phil Solomon, Linda Sparke, Laird Thompson, Rodger Thompson, Harley Thronson, Charles Tolbert, Hugh Van Horn, Gerrit Verschuur, Thomas Weldon, Gart Westerhout, George Withbroe, Sidney Wolff, Andrew Young, Michael Zeilik.

VIII. REFERENCES

Abrams, G.S. et al. 1989. Phys. Rev. Lett. 63, 2123

Abt, H.A. 1990. Publ. Astron. Soc. Pacific 102, 368 Barrett, A.H.

P.C. Myers, & N.L. Sadowsky 1978. "Microwave Thermography of Normal and Cancerous Breast Tissue" Proc. 3rd Intern. Symp. on Detection and Prevention of Cancer (Decker: New York)

Bracewell, R.N. & A.C. Riddle 1967. Astrophys. J. 150, 427

Cooper, B.F.C. 1976. "Autocorrelation Spectrometers" Meth. of Exp. Phys. 12B, 280

Ellis, S.D. 1988. Enrollments and Degrees, Publ. No. R-151,25, Amer. Inst. Phys. NY Ellis, S.D. & P.J.M.

Mulvey 1989. 1987-88 Survey of Physics and Astronomy Bachelor's Degree Recipients. Publ. No. R-211.20, Amer. Inst. of Physics, New York

Kelley, R.L. 1987. "Atomic and Ionic Spectral Lines Below 2000 Angstroms" J. Phys. Chem. Ref. Data 16, Suppl. No. 1

Kidd, J.S. 1989. Scientometrics 15, 241

Malin, D.F. 1982. "Photographic Image Enhancement and Reduction: A Unified Optical Approach" J. Phot. Sci. 30, 87

Malin, D.F. 1990. Kodak Techbits, 1990 Issue No. 1, 1-10

O'Neill, T.J. et al. 1989. Science 244, 451

Reiger, E. et al. 1989. Science 244, 441

Staelin, D. 1980. "Passive Microwave Techniques for Geophysical Sensing of the Earth from Satellites" IEEE Trans. Ant. & Prob. AP-29, 683

Steigman, G. 1989. Ann. NY Acad. Sci. 571, 1 (14th Texas Symposium)

Trimble, V. 1988. Publ. Astron. Soc. Pacific 100, 646

Turco, R.P. et al. 1983. Science 222, 1283

Weinreb, S. "Digital Spectral Analysis Technique and its Application to Radio Astronomy" MIT Research Lab of Electronics, Tech. Report 412, 1963

Weinreb, S. & A.R. Kerr 1983. "Cryogenic Cooling of Mixers for Millimeter and Centimeter Wavelengths" IEEE Journal of Solid State Circuits SC-8

STATUS OF THE PROFESSION PANEL

PETER B. BOYCE,* American Astronomical Society, *Chair* AP923472
CHARLES A. BEICHMAN,* Institute for Advanced Study, *Vice-Chair* ii969352

HELMUT A. ABT,* National Optical Astronomy Observatories – NK158890
WENDY HAGEN BAUER,* Wellesley College – WM362625
GEOFFREY BURBIDGE,* University of California, San Diego – CD305309
ANITA L. COCHRAN,* University of Texas, Austin – TT636128
ROBERT DORFMAN, University of Maryland – Mi915766
HUGH HARRIS,* U.S. Naval Observatory – NR302441
ROBERT HAVLEN,* National Radio Astronomy Observatory NK-855144
CHRISTINE JONES, Smithsonian Astrophysical Observatory – SN747572
JEFFREY L. LINSKY, University of Colorado, Boulder
JULIE LUTZ,* Washington State University
LEE G. MUNDY,* University of Maryland
COLIN A. NORMAN, Space Telescope Science Institute
PATRICK S. OSMER, National Optical Astronomy Observatories
JAY M. PASACHOFF, Williams College
BENJAMIN PEERY, Howard University
R. MARCUS PRICE, University of New Mexico
HARRY SHIPMAN,* University of Delaware
JILL C. TARTER,* NASA Ames Research Center
HARLEY THRONSON,* University of Wyoming