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Future Prospects for Gamma-Ray Astronomy

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FUTURE PROSPECTS FOR GAMMA-RAY ASTRONOMY

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As γ-ray astronomy moves from the discovery phase to the exploratory phase, the promise of γ-ray astrophysics noted by theorists in the late 1940's and 1950's is beginning to be realized. In the years to come, satellites should carry instruments which will have over an order of magnitude greater sensitivity than those flown thus far, and, for at least some portions of the γ-ray energy range, these detectors will also have substantially improved energy and angular resolution. The information to be obtained from these experiments should greatly enhance our knowledge of several astrophysical phenomena including: the very energetic and nuclear processes associated with compact objects, astrophysical nucleosynthesis, solar particle acceleration, the chemical composition of the planets and other bodies of the solar system, the structure of our galaxy, the origin and dynamic pressure effects of the cosmic rays, high-energy particles and energetic processes in other galaxies especially active ones, and the degree of matter-antimatter symmetry of the universe. The γ-ray results of the forthcoming programs such as GAMMA-I, the Gamma Ray Observatory, the γ-ray burst network, Solar Polar, and very high energy γ-ray telescopes on the ground will almost certainly provide justification for more sophisticated telescopes. These advanced instruments might be placed on the Space Platform currently under study by NASA.

1. INTRODUCTION

This meeting has provided an excellent opportunity to review and summarize the current status of γ-ray astrophysics from the lowest to the highest observed frequencies in the γ-ray region of the electromagnetic spectrum. It has come at a very opportune time in that the results of the satellite and other experiments of the 1970's which have formed the foundation for this field may now be examined before the major advances which should be forthcoming in the 1980's with GAMMA-I, the planned Gamma Ray Observatory, improved high energy ground instruments, and other experiments to be carried on balloons, Spacelab, and other space vehicles. The interpretation and understanding of the existing results is being aided by the substantial theoretical work that has already been performed in this field. Theorists have been stimulated to examine processes involving γ-rays in astrophysics, since these photons permit the direct study of the largest transfers of energy occurring in astrophysical processes. These include rapid expansion processes, explosions, high-energy particle acceleration, gravitational accretion onto superdense objects, the fundamental processes of the building of the elements, and even particle-antiparticle annihilation should antimatter by sufficiently abundant anywhere.

Another attractive feature of γ-ray astronomy is that the Universe is largely transparent to γ-rays. They can reach the solar system from the galactic center, distant parts of the Universe, and dense regions near the centers of active galaxies, regions which cannot be viewed in the optical or low-energy X-ray region. This remarkable window extends from a few times 10^7 eV, below which it begins to close slowly as the energy decreases, to 10^{15} eV at which point there begins a one to two decade region in energy wherein γ-ray interactions with the black-body radiation are important.

The high energy γ-ray telescopes carried on SAS-2 (e.g. Fichtel et al. 1975 and Bignami, Fichtel, Hartman, and Thompson 1979) and COS-B (e.g. Mayer-Hasselwander et al. 1979 and Wills et al. 1980) took high energy γ-ray astronomy from the discovery phase to the exploratory phase providing a general picture of the galactic plane in γ-rays identifying sources and general structure, the general character of the extragalactic diffuse radiation, and the first results for γ-ray emission from a quasar. Solar nuclear γ-ray lines have been detected, by Chupp et al. (1973) from the large solar flares of August 4 and 7, 1972 with an instrument flown on OSO-7 and more recently with the SMM satellite from three other flares (Chupp 1980). Successful measurements of γ-ray emissions from the Moon, Mars, and Venus have been carried out during both United States and Soviet spaceflight missions. Also, in the low energy γ-ray region of the spectrum, there has been the discovery of the low energy γ-ray bursts (Klebesadel, Strong, and Olsen 1973). The nature of these γ-ray burst sources remains a puzzle. In the very high energy region of the γ-ray spectrum, ground based Cerenkov light reflector telescopes have good evidence of γ-ray emission from the Crab Nebula pulsar 0531+21 (Helmken, Grindlay, and Weekes 1975 and Gupta et al. 1978), the Vela pulsar PSR 0833-45 (Bhat et al. 1980), Cygnus X-3 (Vladiminsky et al. 1975), and Centaurius A (Grindlay et al. 1975) above 10^{11} eV.

These astronomical γ-ray observations and the many others obtained during the last decade or more give us a more certain basis for considering the possible results which may be forthcoming during the 1980's and the impact that they may have on astrophysics than existed a decade ago when one had only the uncertain predictions of the theorists and a few early results. The synergistic nature of astrophysics strongly suggest that the anticipated γ-ray results will have a major impact on all of the other astronomical disciplines

from the radio to the X-ray realm. This impact should be particularly strong in view of the unique nature of γ-rays in their direct relationship to the high energy processes of the Universe.

In the next section, some of the scientific returns that might be expected from the larger improved γ-ray instruments of the forthcoming decade will be considered. This discussion will be followed by a consideration of the γ-ray telescopes and missions that are anticipated during the forthcoming decade and what they may achieve.

2. THE SCIENTIFIC POTENTIAL OF GAMMA RAY ASTROPHYSICS

The potential for γ-ray astronomy is high in the study of our solar system, our galaxy, and the objects in it, and the radiation coming from beyond our galaxy. In each case, specific areas of major anticipated advancement can be identified. However, it should also be remembered that advances in astronomical instruments in the past have brought unexpected discoveries. Whereas, it cannot be predicted what they will be, it seems very likely that many surprises are ahead for γ-ray astronomy both because it is a young field and because it is so directly related to nuclear phenomena, high energy particle physics, and very energetic phenomena.

(a) The Solar System

It has often been noted that the proximity of the sun makes it of great astrophysical interest because it is a star that can be studied in great detail. One of the specific objectives of solar γ-ray astronomy is the study of the high energy processes that occur in the outer region of the Sun's atmosphere and the relationship of these phenomena to the basic problems of solar activity. A measurement of the intensities of discrete γ-ray line

emissions will reveal the detailed dynamics and time structure of solar flares and energetic particle acceleration. Further, such data should yield qualitative, and in some cases quantitative, information on the composition of specific ambient or transient nuclides in the outer regions of the Sun's atmosphere.

An important aspect of the origin and evolution of the solar system is the determination of the chemical composition of the surfaces of the planets, moons, comets, and asteroids. Measurements of discrete line X-ray and γ-ray emission from condensed bodies in space can be used to obtain both qualitative and quantitative elemental composition information. During the Apollo 15 and Apolla 16 flights in 1971 and 1972, approximately 20 percent of the lunar surface was mapped for magnesium, aluminum, thorium, potassium, uranium, silicon, titantium, and oxygen (Metzger et al. 1973; Adler et al. 1972; Bjorkholm et al. 1973). A γ-ray spectrometer aboard the Soviet Mars-5 orbiter obtained several hours of data, from an altitude of about 2300 km, indicating that the average potassium, uranium, and thorium content of the regions surveyed corresponds to that of terrestrial rocks like oceanic basalts (Surkov et al. 1976). Three Soviet spacecraft, Venera 8, 9, and 10 have carried a γ-ray spectrometer to measure potassium, uranium, and thorium, at the surface of Venus by detecting thorium decay of these naturally radioactive elements (Surkov 1977). Direct comparisons of the results obtained from the lunar samples collected during the Apollo program show that this "chemistry at a distance" approach leads to quite reliable results.

(b) The Galaxy

The existing knowledge on both the diffuse emission and source emission from galactic sources suggest that the next steps in galactic γ-ray astronomy

may be particularly rewarding. A number of high-energy γ-ray galactic point sources have been established, and there have been over two-dozen localized excesses identified by COS-B (Wills et al. 1980). Many of the latter can reasonably be expected to be point sources, and, therefore, instruments to be flown in the future with greater sensitivity and angular resolution should reap a significant crop of γ-ray point sources. By measuring their properties, the nature of the mechanisms capable of generating 10^{34} to over 10^{36} erg s^{-1} for sources such as PSR 0531+21, PSR 0832-45, and Cygnus X-3 (e.g. Kniffen et al. 1974; Bennet et al. 1977; Thompson, et al. 1977; Lamb et al. 1977) in the form of high energy γ-rays can be determined. In the next decade, there should be the chance of studying neutron stars, black holes, pulsars, and supernovae in the γ-ray region where the high energy processes associated with these objects should very likely be most clearly revealed. The detailed study of the gamma ray pulse profile and the variation of the gamma ray spectrum with pulse phase should contribute to the understanding of particle acceleration and interaction in the magnetosphere of rotating neutron stars.

As another example, there are now thought to be several ways that the presence of a black hole might be revealed, and much of the predicted radiation falls in the range of γ-rays. In addition to several different predictions of continuous γ-radiation from a black hole, there is also the prediction of a very unique γ-ray burst at the death of a small black hole; some of these bursts should be detectable with a large high energy γ-ray instrument.

Further, there is the possibility based on theoretical calculations of the observation of γ-ray lines particularly perhaps from supernovae and, hence, the establishment of the sites of nucleosynthesis. Various theories have also

predicted lines, most commonly the half MeV line from electron-positron annihilation, from compact objects.

The high energy diffuse radiation from the galactic plane resulting from the interaction of the cosmic rays with interstellar matter and photons provides the opportunity to study the forces of change in the Galaxy, the origin and expansion of the cosmic-ray gas, and the galactic structure including galactic arms and molecular clouds. Improved angular resolution and sensitivity compared to that which has been achieved thus far in space are required to study the spatial distribution, and better energy resolution is needed to understand more clearly which mechanisms are dominate for the origin of the high γ-radiation. In addition to the diffuse γ-ray continuum existing in our galaxy, it is possible for distinct γ-ray lines to be formed in the intergalactic medium. These lines may be created in several of the following ways: (i) The interaction of low-energy cosmic rays with both interstellar gas and dust grains, (ii) the annihilation of positrons, which have been slowed down, with interstellar electrons, and (iii) the decay of nuclei which in turn emit γ-rays. These are interesting possibilities for the 1980's.

The origin of the low energy γ-ray bursts is unknown, as noted, but they will be included here in the discussion of the Galaxy to make certain they are discussed and to conform with the more conservative current theories. In order to solve the mystery of the nature of the low energy γ-ray bursts, their locations must be established. With the exception of the March 5, 1979 event (Barat et al. 1979; Cline et al. 1980; Evans et al. 1980) which seems unique in many respects, no known X-ray or γ-ray "steady" sources are included in the few well known positions, nor any other known example of exceptional classes of astronomical objects, such as a pulsar or new supernova. It will be important to locate a large number of γ-ray bursts accurately over the next decade if progress is to be made in understanding these bursts.

(c) Extragalactic Radiation

Several types of galaxies such as BL Lacteral objects, Seyfert galaxies, and quasars emit more energy by orders of magnitude than our own galaxy or other galaxies similar to it. The mere existence of these very energetic galaxies together with their proposed explanations seem inevitably to suggest very high energy phenomena, implying that γ-ray astronomy should ultimately make a very important contribution to the understanding of the nature of these galaxies. Since γ-ray astronomy has now moved below the threshold for detection of external galaxies with the observation of NGC 4151, 3C 273, and CEN-A, the next generation of experiments should provide an excellent opportunity to study the high energy aspects of these extraordinary galaxies. Further, straightforward calculations based on the emission from our own galaxy show that about a half dozen normal galaxies should be detectable with γ-ray instruments an order of magnitude more sensitive than those already flown.

A diffuse celestial radiation, which is isotropic at least on a coarse scale, has been measured from the soft X-ray region to about 150 MeV, at which energy the intensity falls below that of the galactic emission for most galactic latitudes. The spectral shape, the intensity, and the established degree of isotropy (although data related to this latter property is very limited) already place severe constraints on the possible explanations for this radiation. For example, these considerations make a galactic halo model interpretation very unlikely.

Among the extragalactic theories for this radiation, the more promising explanations appear to be radiation from exceptional galaxies (e.g., Strong, Wolfendale, and Worrall 1976; Bignami, Fichtel, Hartman, and Thompson 1979) or the γ-ray emission (Stecker, Morgan, Bredekamp 1971; Stecker 1978) from

matter-antimatter annihilation at the boundaries of superclusters of galaxies matter and antimatter, in baryon-symmetric big bang models (Harrison 1967; Omnes 1969; Brown and Stecker 1979). Definitive measurements which could clearly distinguish between these two theories are of major scientific interest. The measurements on the diffuse γ-radiation may, for example, be the only way to determine if the Universe has baryon-antibaryon symmetry.

3. THE MISSION PROSPECTS FOR THE 1980'S

A significant portion of the hopes for γ-ray astronomy in the 1980's are tied to the Gamma Ray Observatory proposed by NASA for an FY81 new start. Other satellite missions devoted to γ-ray astronomy or carrying γ-ray instruments include GAMMA-I, the pair of Solar Polar satellites, the Venera series, possible planetary and cometary missions, other satellites carrying burst detectors, and possibly an advanced solar observatory and the Space Platform later in the decade. It is also hoped that there will be improved ground level telescopes for the very high energy γ-rays.

(a) GAMMA I

The next γ-ray satellite expected to fly is GAMMA I, which is a joint effort of four Soviet and two French laboratories and is to be launched in the early 1980's on a Soviet satellite. It is similar to SAS-2 and COS-B in the sense that its central element is a multilayer spark chamber system, triggered by a directional counter telescope, and surrounded on the upper end by an anticoincidence system. The sensitive area is about 1600 cm^2 or about 2 2/3 times SAS-2 or COS-B; the area solid angle factor is about the same because the viewing angle is smaller. It has an energy-measuring calorimeter which should be able to measure energies with significantly better accuracy than the

energy-measuring element on COS-B. The γ-ray arrival direction will also be measured with greater accuracy. The upper spark chamber system is a twelve-level wide gap Vidicon system. The directionality of the electrons is determined by a time-of-flight system rather than a directional Cerenkov counter. The time-of-flight system approach to the directional measurement, which will also be used in the high-energy γ-ray telescope to be flown on the GRO, has proved to be an order of magnitude more efficient in rejecting undesired events than the previously used directional Cerenkov systems. Because of the space required, it could not have been incorporated in the earlier missions, even if the low power spaceflight quality electronics had been developed.

The improved sensitivity and γ-ray directional accuracy should allow better definition of the characteristics of the galactic plane and provide better position information on many or most of the localized excesses already observed, as well as possibly adding to the number of observed extragalactic sources.

(b) Gamma Ray Observatory

The Gamma Ray Observatory is a mission planned by NASA for a new start in 1981, if approved, and a launch in the mid-1980's. There would be several large γ-ray experiments which together would study six decades of energy ranging from 0.03 MeV to 3×10^4 MeV, with a major increase in sensitivity over previous satellite experiments. The scientific goals of this mission can be summarized as follows:

i. A study of the dynamic, evolutionary forces in compact objects such as neutron stars and black holes, as well as γ-ray emitting objects whose nature is yet to be understood.

ii. A search for evidence of nucleosynthesis - the fundamental building process in nature - particularly in the environment of supernovae.

iii. The exploration of our galaxy in the γ-ray range particularly with regard to regions difficult to observe at other wavelengths, the origin and dynamic pressure effects of the cosmic rays, and structural features particularly related to high-energy particles.

iv. The study of the nature of other galaxies in the high-energy realm and especially the extraordinary ones such as radio galaxies, Seyfert galaxies, and QSO's.

v. The study of cosmological effects through the detailed examination of the diffuse radiation and the search for primordial black hole emission.

These scientific goals necessarily require a set of large individual experiments since several instruments are required to cover the entire energy range and all must have a significant increase in size over earlier satellite experiments to achieve the desired increase in sensitivity. It is advantageous to combine the required instruments into one mission not only because they place similar requirements on a spacecraft, but also because of the very great scientific value of studying the entire spectrum of any object at the same time to examine in detail the nature of time variations.

The combined compliment of instruments to be incorporated into the Gamma Ray Observatory is expected to have the capability to carry out the following:

i. A survey of high energy γ-ray sources and diffuse emission with a point-source sensitivity of 10^{-7} photon cm^{-2} sec^{-1} or better, angular resolution of about 0.1° for strong sources, and energy resolution around 15° at energies above ~10^2 MeV.

ii. A survey of γ-ray sources and diffuse emission with sensitivities around 10^{-5} photon cm^{-2} sec^{-1} and energy resolution around 10 precent at energies between 0.1 and 30 MeV.

iii. Detection and identification of nuclear gamma lines with an energy resolution of <0.4 percent and sensitivity of the order of 5×10^{-5} photon cm^{-2} sec^{-1}. The initial subjects of observation will be the interstellar medium and supernova shells.

iv. Observations of γ-ray bursts, including studies of their spectral and temporal behavior.

The technology to build the appropriate instruments exists, and a set of instruments has already been selected for the study phase by NASA.

Although the specific spacecraft for the GRO has not yet been selected, its capabilities are dictated by the mission scientific requirements. The spacecraft must be capable of accommodating approximately 6500 kilograms of instruments and must supply about 400 watts of experiment power. The 32 kilobit data rate will be supported through NASA's Tracking and Data Relay Satellite System. Celestial pointing to any location on the sky will be maintained to an accuracy of 0.5° with the knowledge of the pointing direction determined to an accuracy of two arc minutes. Absolute time will be accurate to 0.1 milliseconds. The attitude and timing data together with orbital position will be encoded into the telemetry data.

(c) Gamma Ray Burst Detectors

The two Solar Polar missions of ESA and NASA to be launched in the mid-1980's when combined with the satellites close to the Earth, including GRO, will provide a powerful long baseline network for the accurate location of the low energy γ-ray bursts. The Venera series and possible planetary, cometary, or astroid satellites can contribute to this network in an important way. The long baselines available in this network together with the already existing accurate timing should provide substantially improved position determinations, which should clearly identify the objects from which these bursts come if they are in fact clearly seen at other wavelengths.

In addition to the excellent positional determination to be obtained by this network, the presently planned GRO burst detector will be able to observe time variations down to 0.1 ms for strong sources and to detect spectral variations on relatively short time scales. These observations will allow the study of models of emission mechanisms and source geometry in detail. For example, models based on radioactive decay, cooling of a hot plasma, and synchrotron emission following sudden injections of relativistic electrons

into a strong magnetic field would each predict different spectral variations during a burst. The GRO instrument will also contribute in another way. The detectors on interplanetary spacecraft are, of necessity, small and relatively insensitive. As a result, only the strongest bursts can be located by the network being discussed. However, numerous additional bursts that are too weak to be detected by the interplanetary network will be detectable with the large area monitors aboard GRO. Their positions may be determined to about one degree or better by comparing the responses of individual detectors pointed in different directions. The detection of hundreds of γ-ray bursts in the two year lifetime of GRO will allow an accurate determination of the distribution of these sources.

(d) Solar System Studies

Although several solar, planetary, and cometary missions have been discussed, the two Solar Polar satellites are currently the only ones approved in the NASA and ESA programs beyond those already in space. Each will carry a scintillation detector to measure the time history of solar γ-rays and four-channel energy resolution in the range from 15 to 150 keV. The energy spectral information will be obtained every 12 seconds. The results should aid markedly in the study of the fundamental nature of the acceleration, storage, and escape processes of energetic electrons in solar flares. In addition, the possibility of an Advanced Solar Observatory is being considered, and it would hopefully include a discrete γ-ray line detector, which would augment the results currently coming from the Solar Maximum Mission.

(e) Very High Energies

As mentioned earlier, at extremely high energies (above about 10^5 MeV), photons can be detected by instruments at sea level which record the Cerenkov

light produced in the atmosphere from a series of interactions initiated by a single incident γ ray. These telescopes are able to scan a region of the sky where a source is suspected, and make an attempt to detect a directional anisotropy among the air showers which is statisticially significant. Several techniques have been used to enhance the sensitivity primarily by improving the signal to noise ratio (Porter and Weeks 1977), and others may be implemented in the future at a relatively modest cost. A technique using two parallel large reflectors, each equipped with multiple detector channels to provide two images of the shower in Cerenkov light, appears to be one of the more promising approaches for the future (Weekes and Turver 1977).

The search for additional very high energy γ-ray sources and the measurement of their properties including the time history and at least some spectral information is of fundamental importance in understanding the processes in nature which can lead to 10^{11} eV γ rays. Their mere existence has been a surprise to some astrophysicists.

(f) Space Platform

Current NASA concepts for the Space Platform envision free-flying structures, designed for lifetimes of at least a decade, consisting of a central module (containing control-moment gyroscopes and communications equipment) attached to a substantial solar-power unit. Appropriate docking fixtures would permit the simple attachment of a number of pallets functionally similar to, if not identical to, those used for Spacelab experiments. Platform extension arms would be used to reduce interference between experiments, most of which would carry their own pointing systems for the requisite precision. Shuttle flights, most scheduled for other reasons,

would be able to visit the platform several times a year to reprovision expendable materials, provide repair or replacement of experimental hardware, and boost the platform to higher orbit as necessary. Typically a large instrument could be brought to the space platform, operate there for the order of six months, and then be retrieved.

Whereas this program is not approved, being only in the study phase, there clearly exist areas of space astronomy with requirements for long, low-cost exposures of large payloads for which accessibility for replenishment of expendable materials, repair or replacement of components, and return to Earth for reconfiguration is very desirable if not required. Gamma ray astronomy will be among these areas of space astronomy. With the γ-ray sky surveyed in some depth with the GRO, for example, it will be possible to concentrate on the detailed features of discrete sources and to study carefully limited regions such as clouds, galactic arms, and nearby galaxies. The character of the expansion forces, high-energy processes, nucleosynthesis, and cosmic relativistic particles should then be revealed in fine detail. The full solution of problems related to galactic dynamics, compact objects, supernovae, and the nature of radio galaxies quasars, and other truly exceptional objects will be accomplished by combining these unique γ-ray astronomy results with information from other wavelengths.

Thus subsequent to the GRO, a very large high-energy telescope will be needed that will concentrate for long periods of time on particular sources and limited regions of the sky of special interest. This is necessary to accumulate the statistical volume of data required to resolve spatial and spectral features of the sources in great detail and to study temporal variations continuously over periods adequate to decipher complex dynamic behavior. A large high-resolution nuclear γ-ray spectrometer will also be

required for in-depth study of the γ-ray lines from such processes as radioactivity in supernova remnants, positron annihilation in the galactic disk or extragalactic interactions, lower-energy cosmic rays passing through dense matter, and nucleosynthesis in violent events in distant galaxies. In view of the major potential of γ-ray astronomy for contributions to a wide range of astrophysical problems and the ultimate need for even more sensitive instruments of improved angular and energy resolution, the development of new and improved detector systems should be a key part of the γ-ray astronomy program over the next decade.

4. SUMMARY

Celestial γ-rays have now been seen from the sun, the moon and planets, compact objects, the interstellar medium, and active galaxies. Also detected has been a diffuse radiation of possible exceptional cosmological significance, low energy γ-ray bursts of unknown origin, and a high energy γ-ray source with no obvious counterpart at other wavelengths. Still γ-ray astronomy is a young, growing science, and the potential for fundamental contributions to astronomy and astrophysics in the near future is very large. With the study of cosmic γ-rays, the forces of change, the formative process in the Galaxy and interstellar clouds, rapid expansion processes, explosions, the largest energy transfers, very high energy particle acceleration, and even the fundamental process of the creation of elements are all directly examined. If the mission opportunities that have been discussed here come into being, the results that will be obtained, particularly in combination with those from other areas of astronomy, will provide an entirely new look at our solar system, the Galaxy, and the Universe, giving much better insight into their creation and evolution than is currently available.

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