SCIENTIFIC NEED FOR SPACE ASTRONOMY

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Many scientific justifications for space astronomy have been prepared by individuals and committees during the past three decades or more. The first such report that I am aware of, called "Astronomical Advantages of an Extraterrestrial Observatory", was written by Lyman Spitzer in September 1946, and although its goals were extremely modest by today's standards, the report did dwell with enthusiasm on the ultimate goal of a large reflecting telescope 4-6 meters in diameter with diffraction-limited optics put into earth-satellite orbit. The latest study, from which I shall quote liberally, has just been published by the Astronomy Committee of the U. S. National Academy of Sciences, and provides the scientific foundation for space astronomy in the 1980's. Space Astronomy was initiated about one month after the date of publication of Spitzer's report, when the first high-altitude rocket was launched to observe the sun's ultraviolet radiation. Since that time, space astronomy has completed two phases and is about to embark on a third. In Phase 1, which lasted until the beginning of Sputnik, observations were made for a few minutes at a time from high-altitude rockets. In the second phase, which is just ending, observations were made with relatively small instruments in earth-orbiting satellites. The observing programs carried out with rockets and small satellites were called *experiments* because their capabilities and objectives were limited and their lifetimes were short - from a few minutes to about a year.

Until now, we have not taken full advantage of the benefits of operating in space, particularly as regards sky noise and high spatial resolution. In Phase 3, which is about to begin, both of these advantages will be fully explored, and moreover technical advances in gamma-ray and IR detection will open wide these regions of the spectrum. Observations will be carried out not with experimental apparatus but with large and sophisticated instruments, some of which will be remotely operated more or less permanently in orbit, although designed to be repaired, maintained and upgraded *in situ* or on Earth. Other telescopes will be installed in flying laboratories which can be transported into orbit with observers and technicians on board and then returned to earth after a week to a month for refurbishing and reflight.

Many of the missions that will fly in the new era of space astronomy have already been planned or approved for the 1980's, among them IRAS, ST, SOT, SIRTF, and the out-of-ecliptic solar mission. Other advanced missions are already within the range of existing technology, e.g., a very large optical telescope (10-25 meters), a long-baseline optical interferometer,

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a gamma-ray observatory, a 1 to 1.5 meter aperture X-ray telescope, etc.

The scientific case for these and other missions can be documented on a number of different levels of scientific and technical detail; for example, I could simply list the environmental advantages of observing in space, as compared with the best sites on the ground:

1) Access to entire electromagnetic spectrum.
2) 100% clear sky.
3) Freedom from bad seeing.
4) Freedom from sky-background noise.
5) Freedom from gravity in the construction of large telescopes.
6) Use of large diffraction-limited optics.
7) etc., etc.

It all depends upon whom we are persuading. For observational astronomers, there would be no need to go any further because what I have described is the astronomical equivalent of heaven. Unfortunately, until we get to the real heaven, we shall be restricted by financial considerations and costly space projects will have to be justified in terms of the expected scientific benefits.

One way of describing these benefits is to explain how the advantages of operating in space can be translated into enormous gains in observing capability. For example, by studying cosmic rays, gamma rays, and X-rays, we revolutionize our knowledge of high-energy processes in the Universe, both in the Sun and the most distant regions, by observing the hottest gases in the Universe and such phenomena as the interactions between relativistic particles and matter, matter-antimatter annihilation, and nucleosynthesis. Diffraction-limited optics with images as small as $0\overset{''}{.}1$ placed above the airglow enormously extend the limits of observation at optical wavelengths and large, cooled IR and submillimeter telescopes above the atmosphere can observe matter as cold as 3°K. And so on.

This should be all the justification that any reasonable person might want but surprisingly it is not. The best way to get a large project approved is to show that it is relevant to solving a fundamental problem, which translates into solving the problem of the origin and evolution of some object, such as the Sun, the Moon, the Solar System, the Galaxy - or the entire Universe. Even the 200-inch telescope was claimed to have been needed because it would make possible the determination of the parameters of the Expanding Universe. In the same way, the Apollo missions were supposed to discover the origin and evolution of the Moon, while the Pioneers, Mariners and Voyagers are being sent to reveal the origin and evolution of the solar system.

It seems to be taken for granted that every large telescope proposal, whether on the ground or in space, must include a justification that explains its importance to our understanding of the origin and evolution of the Universe. For this, a working model is needed and the most popular one is that of the hot, expanding universe, otherwise known as the Big Bang. I personally find it hard to understand how a model formulated in the 1930's has managed to withstand the shock of the really fantastic discoveries that have been made over the past 25 years. Perhaps these discoveries have not been so revolutionary after all, because they seem not to have changed our fundamental ideas on how the Universe started and evolved to the present time. Or perhaps the sheer simplicity of the model is so appealing that its shortcomings have been overlooked.

But for our purposes it really matters little which model we choose, even between two as disparate as the Friedmann-Lemaitre and Klein universes. The observations that are now, or soon will be, possible from space will almost certainly destroy both of them, because for the first time in history cosmology will be put on a reasonably firm observational basis.

So let us proceed to illustrate the scientific importance of space astronomy by showing how it can test the Big Bang model at almost every point in its evolution, from the first few minutes to the present time 15 billion years later, including the formation of D and He, the observation of relict radiation, the formation and evolution of galaxies, the formation of stars and solar systems, the formation of heavy elements in stellar interiors, the enrichment of the interstellar medium with heavy elements by supernovae, novae and stellar winds, and the final stages of stellar evolution. In this account, I shall be extremely selective in the choice of problems and both brief and arbitrary in describing the unique contributions of space to their solution.

In the area of cosmology, it is vital to establish whether or not the fireball radiation fits a black body curve and this can be done by extending the spectral measurements to the high frequency side of the intensity maximum. The absence of sky noise will be very important and will facilitate the detection of small anisotropies from which could be derived the peculiar velocity of our Galaxy and the effects on the expansion of local concentrations of mass such as the Virgo cluster. The accuracy of the cosmological distance scale can be greatly improved by the observation of Cepheids in galaxies well beyond the present limit of 1/5 the distance to the Virgo cluster. This is made possible because, with the spatial resolution of 0.1 arcsecond, the brightness of the stellar background is reduced by a factor of 100. The use of bright stars, supernovae, H II regions, and surface brightness, can also be greatly extended. The problem of the mean density of matter, determining whether the Universe is open or closed, can be clarified by accurate measurements of the X-ray, ultraviolet and optical background. The X-ray and UV background is thought to be emitted by intergalactic material and the optical and IR background by extragalactic radiation. We note that far away galaxies should be very bright at 1 μm ; therefore it is quite important to observe from above the airglow.

If most of the helium and deuterium in the Universe were created before the galaxies were formed, their abundances would be expected to be the same in all galaxies. Finally, the search for evidence anywhere in the Universe that anti-matter and matter are symmetric is one of the most important undertakings for gamma-ray astronomy.

Going now to the question of the formation and evolution of galaxies, high resolution observations above the airglow should make it possible to study the appearance of galaxies as far back in time as $z = 1$, which is about half the age of the Universe, and to detect variations with time of luminosity, activity, and degree of clustering. Moreover, the appearance of the sky at very high z might be inferred from the absolute brightness of the background at all wavelengths from ultraviolet to far infrared (100 microns). Finally, X-ray measures on clusters of galaxies at $z \gtrsim 1$ would map the distribution of the intra-cluster gas and perhaps reveal whether it originates by accretion or by stellar mass loss.

One of the most exciting prospects for space astronomy during the next ten years or so is the development of spatial interferometers for visible and infrared wavelengths. Such devices, with a spatial resolution of 0.01 arcsecond, could in principle observe the earliest stages of star formation, namely the fragmentation and collapse of cold interstellar clouds. The spectra of proto-stellar objects would be observed more easily, but interferometric resolution would be still needed at infrared wavelengths. Infrared imaging with high spatial resolution might also reveal the presence of other solar systems. I must also mention the importance of high resolution observations of solar system objects - planets, satellites, asteroids and comets - by telescopes in earth orbit or by close approaches of instrumented spacecraft, in illuminating the origin of the solar system and its relation to star formation generally.

The interstellar medium is clearly an important key to the understa-nding of star formation. The recognition that the interstellar medium has a hot component with $T = 10^5 - 10^6$ °K is one of the more notable recent achievements of space astronomy. The properties of the hot medium can be deduced from observations of the O^{VI} absorption lines and the diffuse background of soft X-rays. The derivation of element abundances need to be extended to the more distant stars such as those in other spiral arms and in the halo of our own galaxy and in nearby galaxies. The abundances of atomic elements can be derived from ultraviolet absorption spectra and from absorption edges in bright X-ray sources. We can also look forward to the detection and analysis of forbidden transitions and molecular lines with a large infrared cryogenic telescope. The distribution and composition of both gas and grains can also now be studied from γ-ray lines emitted as a result of interactions with cosmic ray nucleons. The de-excitation of nuclei in grains produces a number of very narrow lines, for example O^{16} at 6.129 MeV. A search for new atomic and molecular species could profitably be undertaken by a large submillimeter-wave radio telescope in space.

The energy production and radiation mechanisms in active galaxies and quasars are still a complete mystery and need systematic investigation by measurement of brightness and polarization across the entire spectrum from γ-rays to radio waves. The role of magnetic fields and the energetics of particles may be inferred from the emission of X-rays and γ-rays. For example, the detection of γ-ray lines at 4.4 MeV and 1.6 MeV from Cen A may imply the existence of quasi-thermonuclear reactions near a black hole.

The highest possible spatial resolution is needed to study the geometry of the sources, which is so important from the standpoint of energy prod-uction. A spatial resolution of 0.1 arcsecond will be an important step but probably real progress will have to wait for a spatial interferometer.

Any working model for stellar evolution presupposes that we know how energy is generated and transported through the stellar interior. Recent studies of the Sun have shaken our confidence in this respect and, therefore, gaining knowledge about stellar interiors should have a high place on the agenda for space research. The Sun is the most promising object for this purpose, and observations in recent years with vacuum telescopes under good seeing conditions have demonstrated the importance of high spatial resolution, about 0.1 arcsecond, which cannot quite be reached from the ground. Such resolution is needed for the study of oscillations in diameter and velocity and of magnetic fields in sunspots and very small knots. A variety of approaches can be taken to study the interiors of other stars, as faint as the lower main sequence in globular clusters and the horizontal branch in the Magellanic Clouds. For example, accurate distances and therefore absolute luminosities can be obtained from parallaxes and proper motions with high spatial resolution and low background noise. Element abundances, especially of rare isotopes, can tell us much about nuclear processes and interior mixing. Activity cycles of other stars can probably best be studied from X-ray fluxes which in the case of the Sun show very large variations in amplitude, by a factor of 10 - 100. Surface features of at least supergiants may be observable with a very large aperture telescope or interferometer in space. Finally, very high spatial resolution will greatly expand our knowledge of binary star orbits and masses, to help us better understand stellar structure.

For stars more massive than 1.4 solar masses, mass loss is the critical factor in determining the end point of stellar evolution. Although the more massive stars do lose enough mass by stellar winds to affect their evolution significantly, neither the amounts of the mass loss nor the mechanisms are known with high accuracy. It will be possible with the Space Telescope to study mass loss in hot stars as faint as horizontal branch stars in globular clusters and supergiants in other galaxies. When infrared imaging with high resolution becomes possible, the dynamics of the gas and dust flows, including the role of radiation pressure in accelerating circunstellar matter, should be considerably clarified. We cannot evaluate the importance of thermally-driven winds in late-type stars without a better understanding of the mechanism of solar coronal heating, and the origin of coronal holes and high-speed wind streams. All the signs point to the importance of high spatial resolution in the observation of magnetic fields and gas flows as the key to the solution of this problem. The possibility of observing the Sun in the direction of the poles with the so-called out-of-ecliptic probe is particularly exciting.

In the last stages of a star's evolution it may become either a white dwarf or a supernova leaving behind a residual neutron star or black hole. One way of determining how massive stars can be and yet evolve into white dwarfs would be to establish white dwarfs as members of young clusters. This requires measurement of proper motions smaller than 0.01 arcsecond per year for stars as faint as 20th magnitude. Another exciting prospect is to identify a number of compact X-ray sources as accreting dwarfs both with and without strong magnetic fields. The mass and magnetic field may be derived from the luminosity and the spectra respectively.

A wealth of important information can be obtained from space observations of supernovae including the chemical abundances of the ejecta, the nucleosynthesis of iron group elements from observations of γ-ray lines, isotope

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abundances from cosmic rays and nuclear particle acceleration in supernova remnants by observation of gamma rays from Π^0 decay.

Neutron stars can be investigated with a variety of techniques for the observation of high energy processes. Hard X-ray spectra have already provided estimates of magnetic fields in the neighbourhood of 10^{12} gauss. Both the existence of non-magnetic neutron stars and the mass range over which neutron stars occur can be studied in binary X-ray sources. Observations of γ-rays could reveal to what extent cosmic rays originate from particle acceleration in rotating, magnetized neutron stars. Other X-ray sources similar to Cyg X-1 need to be discovered and investigated to establish the existence of black holes.

Finally, the study of solar flares with high spatial resolution over the entire energy spectrum presents an absolutely unique opportunity to study the particle acceleration mechanisms that are so important in all branches of high-energy astrophysics. It should be noted that γ-ray lines at 0.511 MeV, which result from positron annihilation, and at 2.223 MeV, which arise from neutron capture on H, have already been observed.

These are but a few examples of how current ideas on the origin and evolution of the Universe may be tested by observations in space. But progress in astronomy does not follow alone from the testing of theories. Ours is an observational as well as an experimental science and surveys of the sky with new observational techniques have always been of extreme importance in the advancement of astronomy. For example, neither quasars nor pulsars, nor accreting stars as X-ray sources, nor infra-red radiating dust shells were predicted in advance by theory. They were discovered by survey-type instruments, and there is still an important need to search for interesting and novel objects that radiate in various parts of the spectrum. For example, the wide-field all sky surveys carried out at Palomar and by ESO and SRC need extension to the far UV, say to 1500 Å. A deep infrared survey in four wavelength bands, 10μ, 25μ, 60μ and 100μ is already scheduled for 1981 with the IRAS satellite. A survey for gamma ray sources over a wide energy range should have very high priority in the near future.

Finally, I want to take note of the possibilities for doing a number of physical experiments of a fundamental nature, which can be advantageously undertaken in space, but which are not usually regarded as belonging to astronomy. Among the experiments that have been proposed are several in the area of gravitation and relativity, e.g., measurement of the curvature of space caused by the Sun's mass at the distance of the earth, by measuring the precession in earth orbit of gyroscopes cooled to liquid He temperatures, measurement of a possible secular change of the gravitational constant (increase of the lunar period by 2 - 6 parts in 10^{11} per year), a repeat of the Cavendish experiment in space, leading to a more precise determination of G, etc. Some of these experiments are already being designed and built.