INVESTIGATION OF SMALL SOLAR SYSTEM OBJECTS WITH THE SPACE TELESCOPE

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One of the prime motivations behind astronomical research in general, and utilization of the Space Telescope in particular, is our desire to understand our ultimate origins. With the ST we expect to find answers to fundamental questions concerning the birth and death of the universe. But another fundamental question of comparable significance deals with more local beginnings. The Sun and its planetary system were formed long after the initial creation, accreting in an obscure corner of our galaxy by processes perhaps less well understood than those of the universal Big Bang. In this paper, I consider ways in which the Space Telescope can contribute to studies of the birth and early evolution of the solar system, through studies of its smaller members.

It is generally believed that the solar system was formed about 4.5×10^9 years ago when a local collapse of a cloud of interstellar material developed a hot central mass, the proto-sun, surrounded by a more tenuous disk of orbiting debris, the solar nebula. The nebula was presumably mostly gas, but it may have included interstellar dust grains which were never vaporized by the proto-sun before general cooling of the nebula permitted widespread condensation of refractory solids. For some period the condensing solids remained in approximate chemical equilibrium with the gas, with composition controlled primarily by temperature. The degree to which chemical equilibrium was reached, or maintained as the grains accreted into larger masses, is a major area of uncertainty. Apparently the growth of solids proceeded rapidly once condensation began, with planetesimals of up to several hundred kilometers diameter formed; these in turn accreted to form the planets and satellites, in the process being mixed and scattered by gravitational interactions. Each planet presumably contains materials from a variety of locations in the nebula, and the record has been further blurred by subsequent heating and differentiation to the point where large bodies retain at best a faint memory

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of the conditions of their birth. In contrast, some of the primitive planetesimals escaped both incorporation into larger bodies and gravitational ejection from the solar system. These remain today as asteroids, small planetary satellites, rings, and comets.

Most of what we know about the formation of the solar system has been derived from these objects, particularly those whose fragments reach the Earth as meteors, meteorites, and interplanetary dust. Detailed chemical and isotopic analysis of these samples in terrestrial laboratories remains the primary tool for this research. But astronomy also plays a vital role in relating the samples to their parent bodies, and in exploring the classes of small solar system objects that are presumably not represented in our randomly acquired collection of fragments that have reached the Earth. The Space Telescope also has an important place. Since the number of basic questions about the small bodies that can be answered by ST is relatively small, these investigations will make modest demands of observing time. However, it is vital that this instrument be used where it has a major capability, since the alternatives are sometimes extremely expensive planetary deep-space missions. In solar system research, we must combine carefully the strengths of laboratory studies, of ground-based astronomy, of observations from Earth orbit, and of dedicated planetary missions in order to achieve our goal of exploration and understanding in an efficient and cost-effective manner.

In the above I have sketched a motivation for studying small objects in terms of their chemically primitive nature, as the least-altered survivors of the original condensations from the solar nebula. But, of course, many small bodies have undergone subsequent chemical evolution of differing degrees, up to the case of Io, which is surely the most thoroughly heated, processed, and volatile-depleted object in the solar system. In the following, I will include studies of the evolved, as well as the primitive, small bodies. The upper size limit for a "small" body is ~5000 km, so as to include the largest satellites, except for Titan, which is considered a planet for purposes of this discussion.

High-resolution imaging is one of the important tools provided by ST for study of small solar-system objects. In the following, I will assume that resolutions of ~0.05 arcsec, or equivalently ~40 km at 1 AU, can be achieved. This resolution corresponds to the pixel size of the Planetary Camera. To achieve it, special image processing will be required; without this effort, the nominal resolution will be about a factor of two worse. The Faint Object Camera has a pixel size a factor of two smaller yet, corresponding to about 0.002 arcsec. For the nominal resolution of the ST optics, this represents oversampling of the point-spread-function, and it is unlikely to yield realizable resolutions this high. However, if the optics perform better than now

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expected, the FOC is likely to provide higher-resolution images than those assumed in this discussion. The actual resolution of any of these instruments, of course, will not be known until ST is actually performing in orbit.

PLANETARY SATELLITES

The 34 known natural satellites in the solar system encompass a remarkable variety of worlds, from Titan with its cloudy atmosphere and Io with its gigantic volcanic eruptions and complex magnetospheric interactions, to thousand-kilometer-diameter ice-balls such as Rhea or Dione, to small objects such as Elara or Phobos that may be genetically related to the primitive asteroids. The study of these objects has grown over the past decade into a major branch of solar system astronomy, and with the Voyager exploration of the Galilean satellites (and unimagined wonders yet to come at Saturn), their continued prominence is assured. Each of the major satellite systems - of Jupiter, Saturn, and Uranus - is a kind of miniature solar system, and we already know for the Galilean satellites that these objects are as varied, and as interesting, as the terrestrial planets themselves.

The most spectacular advances in our knowledge of planetary satellites have come from direct exploration, of Phobos and Deimos from Viking and of the Galilean satellites from Voyager. Generally speaking, these objects are now the province of the geo-scientist, not the astronomer. Where a Mariner-class spacecraft has already explored, there is not a great deal remaining for Earth-based astronomy, except in the study of time-variable phenomena. In the preceding paper Belton has discussed these areas, including the exciting cases of Titan and Io. In this paper, I restrict myself to satellites without atmospheres or extended plasma clouds.

From the geological point of view, images with resolution of about 10-20 km are required for a first-order global perspective, and resolution near 1 km is required to reveal the details of geological processes. The ST cannot approach these resolutions for any outer solar system satellite. For the Galilean satellites, resolutions of ~200 km are possible, but such images could contribute little after Voyager, with the one exception noted below. At Saturn, the resolution is ~400 km; even today, such images would be of only limited interest, and after Voyager they too would be obsolete. There is only one major area in which ST imagery of satellites might be useful, and that is in extending the search for faint inner satellites of Saturn, Uranus, and Neptune. The high spatial resolution, freedom from atmospheric scattered light, and faint limiting magnitude of ST should produce much more complete surveys than have been possible from the ground. The discovery of such inner satellites would have important implications for the origin and dynamical structure of planetary rings. In contrast, the ST will not be used to search for faint outer satellites, which are best located with ground-based, wide-field surveys.

Although the prospects for carrying out geological studies of satellites from ST are weak, there exists a special opportunity to study time-variable phenomena in the case of Io. The largest volcanic fountains or plumes seen by Voyager are 200-300 km high and perhaps 600 km across at the base. At a nominal 200-km resolution, such features might be detectable, with appropriate image processing. If so, ST could make a major contribution to understanding the time-scale for volcanic activity on Io, as well as monitoring the presumed sources of ions to the Io plasma torus and to the auroral zones on Jupiter. Also near the resolution limit, but of comparable significance, would be measurements of albedo and color changes on Io. A major eruption could easily deposit an optically thick layer of pyroclastics and condensed volatiles over an area hundreds of kilometers in dimension in a period of a few weeks. If the new surface contrasted strongly in albedo or color with the old, the change could be seen in ST images.

Both Pluto and its satellite are "small bodies" within the definition of this paper, and both can be investigated profitably with the ST. The planet, with a diameter of only about 3000 km, is barely resolvable. However, its satellite, with a magnitude of about 17 and a maximum separation of about 0.7 arcsec, should be easily separated. A small number of images will yield much improved values for the semi-major axis of the orbit and hence the mass of Pluto, as well as yielding colors and magnitudes for the satellite. Accurate photometry of both planet and satellite can also be obtained with the high speed photometer. Astrometric measurements may allow the mass of the satellite itself to be calculated. Without the ST, there is very little we can do to learn more about the physical nature of this extraordinary planet/satellite pair.

One additional area remains in which I expect the ST to contribute to satellite research. Low-resolution reflection spectroscopy has proved itself as the technique best able to determine the mineralogy of a solid surface, including the identification of both ices and silicates. Most of this work has been done in the infrared, from about 0.7 to 4.5 μm; unfortunately, ST will not be able to contribute much in this area with its initial instrumentation. However, there have been several recent suggestions of the capability of ultraviolet spectra to reveal features diagnostic of surface composition. In the UV, the energy of a photon is of the same order as the valence-conduction band gap in a number of solids of geologic interest, including olivine, ilmanite, calcium-feldspar, and augite. Observations are now being made of some small solar system bodies using IUE; depending on their outcome, there might be observing proposals for ST to extend UV spectroscopy to much fainter satellites, asteroids, and cometary nuclei.

PLANETARY RINGS

Three of the four Jovian planets are known to have ring systems consisting of particles orbiting in the equatorial plane of the planet inside the Roche limit. The Saturn system, first seen by Galileo and identified as rings more than 300 years ago, consists of several concentric planar rings composed primarily of small (tens of centimeters), high-albedo ice particles. The densest part (ring B) has optical depth near unity, and the relatively narrow gaps, corresponding to simple resonances with the inner satellites, are not swept entirely free of particles. The characteristic ring width is tens of thousands of kilometers. The Uranus rings, discovered by stellar occultation in 1977 and since observed as well by reflected light (visible and infrared), are entirely different. The ring particles are of low albedo ($\sim$3%), suggesting carbonaceous chondritic composition. The rings themselves, of which about ten have been identified, are more ribbon-like than planar, with widths of tens of kilometers at most, and maximum optical depths somewhat less than unity. The major (ε) ring is apparently non-circular and precesses rapidly. The ring positions do not coincide with simple satellite resonances. Finally, a third ring system was discovered this year during the Voyager encounters with Jupiter. This system consists of a main ring several thousand kilometers wide with a sharp outer edge, and a second continuous ring about a tenth as bright extending inward to the planet. The surface brightnesses of these rings are very low, suggesting optical depths less than 0.01; nothing is known about the albedo or composition of the particles, except that they seem unlikely to be ice and they have a reddish color. The edges of the main ring also do not correspond to simple resonances with Amalthea or the Galilean satellites.

Perhaps the most immediate question concerning planetary ring systems is whether each of the four Jovian planets possesses one. It is within the capability of ST to answer this question by carrying out a search for a Neptune ring system. Direct imaging in a methane band is likely to detect any but the faintest ring. The rings of Uranus have been detected marginally in this way with a CCD on the University of Arizona 1.5-meter telescope, and the advantages of ST resolution should far outweigh the greater distance of Neptune. Alternatively, the Neptune system might be detected by stellar occultations with the ST High Speed Photometer, although it should be remembered that the cross section for occultations is substantially less than in the case of the high-inclination Uranus rings. Clearly, measurements by both occultation techniques and reflected light are required to begin to characterize the nature of this ring system if it exists.

The rings of Jupiter should be within the imaging capabilities of the Planetary Camera; they have already been detected in their reflected light at 2.2 μm from the ground. The resolution of the camera is ~200 km at Jupiter, possibly permitting measurement of radial structure in the main ring when the system is near its maximum inclination with respect to Earth (~3°). Occultation observations are highly desirable but extremely difficult; without them it is difficult to estimate the optical depth of the rings or the albedos of the individual particles.

The rings of Saturn will be a glorious sight in Planetary Camera images; with a resolution of about 400 km, it will be possible to trace the radial photometric structure in detail and to establish the radial dependence of the large-scale photometric asymmetries between quadrants seen in ground-based photometry. Optical depth profiles can also be traced from stellar occultations, an extremely difficult task from the ground, requiring a rare occultation of a very bright star. Ultraviolet spectra will also be of interest in establishing the nature of the contaminants in the ice that produces the well-known drop in albedo toward short visible wavelengths. However, it is difficult to predict the degree to which all of these studies will still seem relevant after the Voyager flybys in 1980 and 1981. The Voyager resolution and range of viewing geometry will far exceed that of ST. Important questions may be raised that will require ST data for their resolution, or it might turn out that ST has little to contribute after Voyager.

One area of study of the rings of Saturn in which ST has unquestioned superiority is that which concerns the long-term variations associated with the 15-year cycle of ring tilt. Voyager will obtain two snapshots near the time of minimum ring tilt; ST will, however, be able to view the planet year after year as the rings become fully open in about 1988 and then close again toward the 1995 ring plane crossing. In particular, it appears that photometric imagery in 1995 is likely to provide the best data on the physical thickness of the rings and on possible out-of-plane warping that we will obtain in this century.

The rings of Uranus can be studied with the Planetary Camera at much higher resolutions than are available from the ground. Additional occultation profiles of optical depth can also be obtained, although these may not represent a great improvement over occultations observed at 2.2 μm with large infrared telescopes. The acquisition of color data, and perhaps ultraviolet spectra, could help establish the composition of the ring material. And finally, the bizarre nature of the ε-ring is a continuing puzzle, and ST data may play a role in unraveling its dynamical behavior. Occultation measurements of precession rates can also provide data on the gravitational moments of Uranus.

The recent discoveries of rings around Uranus and Jupiter have

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introduced many confusing elements; in general, I would say we understand planetary rings much less well today than we thought we did a decade ago. Both improved data on radial structure and new insights into the dynamical interactions of rings and satellites are badly needed. In such a period of flux, it is especially difficult to predict the effect of a major new instrument such as Space Telescope.

ASTEROIDS

The asteroids or minor planets have become, within less than a decade, one of the most active areas of planetary astronomy. The application of a wide variety of observational techniques to hundreds of these objects has permitted the identification of a variety of compositional types and of their distribution in space, and has established for the first time such basic parameters as the sizes of these objects. Many mineralogical analogs have been found for common meteorite classes, and many of the advances of the past few years have come about through close contact between astronomers and meteoriticists. We now know that the majority (~75%) of the asteroids are chemically primitive (similar to the carbonaceous chondrites), but that mixed among them, particularly in the inner belt, are many objects that appear to be fragments of heated and differentiated parent bodies. An outstanding question, however, remains the identification of the parents of the most common type of meteorite, the ordinary chondrites, for which no link to main belt asteroids has been reliably established.

The main problems in asteroid research today concern geology and geochemistry. We have never "seen" an asteroid in the geological sense; these bodies remain unresolved point sources rather than true planetary bodies or, perhaps even more exciting, fragments of planetesimals that reveal their interior structure. Geochemical relationships also remain more tantalizing than secure, with no clearly established connections between individual meteorites, which reveal such a wealth of data in modern laboratories, and their asteroidal parents. Unfortunately, neither of these areas is likely to be advanced in a major way by ST observations.

The Planetary Camera will have a resolution for a typical main-belt asteroid of about 100 km, not high enough to reveal geological structure. This is sufficient resolution to yield good diameters for the larger objects, but it is not competitive with stellar occultation measurements, and it may be no better than indirect techniques of diameter measurement, such as by infrared radiometry. This resolution is clearly great enough, however, to search for albedo or color variations on the largest asteroids. For 1 Ceres, an image would include about a hundred pixels, for 4 Vesta and 2 Pallas, about 30. Clearly, these three objects should be imaged in several colors, as a first step toward revealing the global structure of a previously unresolved class of objects.

There is an additional area of current concern in which ST can make a major contribution. Based on some recent occultation photometry, it has been suggested that several asteroids, most convincingly 432 Herculina, may be double or multiple. The Planetary Camera can easily resolve this question; the suggested companion of Herculina would be separated from it by more than 10 pixels, and the 3.6-mag brightness difference is well within the range of the detector. One or two ST frames will either lay this problem to rest or else open a fertile new field of research into multiple asteroids.

COMETS

The comets are the most primitive small bodies in the solar system, with the highest ratio of volatiles to solids. Presumably, they condensed early from the solar nebula, and it is probable that even some interstellar grains are incorporated within them. Preserved billions of years in the deep freeze of space, the comets are fed at a slow but steady rate back into the inner solar system. While a single comet may survive only a few hundred perihelion passages before its volatiles are exhausted, the comets as a class are a renewable resource, providing a supply of pristine material from which we can infer the conditions of origin of the solar system.

In spite of their great potential, the comets are in fact poorly understood. We have never measured the nucleus of a comet without its obscuring halo of atmosphere; we do not even know with any precision how big a cometary nucleus is. Most of the volatile materials that are emitted from the nucleus as it is heated by the Sun are also unobserved; instead, we see the molecular fragments of photodissociation and other less well-understood chemical processes. The intricate dynamics of comet tails are controlled by complex plasma processes, as the cometary atmosphere interacts with the solar wind. And even the ultimate fate of comets is unknown; they may evolve into Apollo/Amor asteroids, or perhaps they dissipate into unobservable fragments as their volatiles are exhausted.

A number of important investigations of comets can be carried out with the ST. Some of these involve short-period comets, especially observations of the nuclei at large distances from the Sun when they are not shrouded in gas and dust. These can be scheduled long in advance. However, it is also important that the ST be available to investigate any large, bright comets that may be discovered. Only about one such comet appears per decade, but often there is little warning; ability to reschedule on as short as a week's notice for a

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really spectacular comet could yield important dividends. Finally, there is the special case of Comet Halley, which is the only bright, active periodic comet available for study during the rest of this century. The 1985/86 apparition of Halley will not be well placed for ground-based observations, but the ST will be in an excellent position for study of this object. (It is interesting to note that the last Halley apparition, in 1910, took place before the advent of large reflecting telescopes or even simple photoelectric detectors; in one orbit of Halley, we have gone from the Lick and Yerkes refractors and rather slow photographic emulsions to the construction of a large astronomical observatory in space!) It seems almost certain that the public, as well as the scientific, perception of Halley in 1986 will be based in large part on ST data.

A comet includes phenomena in a wide range of spatial scales, from the nucleus (~1 km) to the tail (~10^8 km). Unfortunately, the nucleus itself will not be resolvable by ST; at a distance of 0.2 AU, the limit of about 10 km is larger than the anticipated size of any but the very largest cometary nuclei. However, fine structure in the coma and the tail should be extremely interesting, especially if some reasonable time resolution is possible. Comets are dynamic objects, and it is important to sample time domains of minutes to days if we are to understand the phenomena.

Ultraviolet spectroscopy with both the High Resolution Spectrograph and the Faint Object Spectrograph will provide the area in which the primary contribution to cometary research can be made with ST. Most of the resonance transitions of the anticipated parent molecules in the inner coma lie in the vacuum UV. The combination of UV sensitivity with high spatial resolution raises the promise for the first time of understanding the composition and chemical processes of the neutral coma. Special spectroscopic studies will also be of interest, including the precision measurement of the ratio D/H for this sample of primitive solar-system material.

Although the nucleus cannot be resolved directly, the ST can contribute uniquely to the study of cometary nuclei by carrying out observations when the nucleus is inactive. The comet could be followed to 6 AU or farther from the Sun, and studied by the photometric and spectroscopic techniques used to determine the surface compositions of asteroids. As an example of the power of ST, I note that it will be possible to observe the nucleus of Comet Halley throughout its orbit, even at aphelion.

A special opportunity for ST observations of comets will become available if there is a NASA deep-space mission to one or more comets in the late 1980's. The most promising such mission opportunity involves a launch in July 1985 and a fast-flyby of Halley near its perihelion, including deployment of a dedicated probe toward the

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nucleus. The primary spacecraft then continues, slowly modifying its orbit with an ion drive low-thrust propulsion system. In July 1988, it achieves rendezvous with the short-period comet Tempel 2. For the next twelve months, it remains close to the nucleus, making detailed observations of the nucleus and the inner coma. During both the Halley and the Tempel 2 phases of the mission, the large-scale perspective provided by ST observations will be needed to complement the detailed, small-scale observations made from the spacecraft. In turn, the *in situ* data will provide a unique calibration of remote sensing by ST and ground-based telescopes, thus greatly increasing their power to study other comets for which there will be no direct exploration by a deep-space probe.

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DISCUSSION

Owen (Discussion leader): Dr. Bradford Smith has already referred to the general goal of understanding the origin and evolution of the solar system as an underlying motivation for many of the investigations we are discussing this morning. Another such goal is the understanding of the origin and cosmic distribution of life. Studies of primitive bodies in the solar system have a direct bearing on both of these questions.

I must disagree with Dr. Morrison's suggestion that only small bodies are primitive. While it is true that the giant planets have not retained the memory of their origin, Jupiter and Saturn may actually represent trapped samples of the original solar nebula itself. If they do, we may also regard them as separated fragments of the interstellar medium that have been preserved for 4.6×10^9 years at temperatures well below the threshold for nuclear reactions, conveniently available for our investigation. We may then have the opportunity to study elemental abundances in great detail, thereby at last obtaining a rigorous calibration for theories of nucleosynthesis and mixing within the galaxy. The high resolution spectrograph on the Space Telescope is bound to make important contributions to these studies.

The lack of original memory to which Dr. Morrison referred pertains to the chemical evolution that is taking place within the atmospheres of these objects. But this evolution is limited by the ability of all four giant planets to retain hydrogen. Thus the chemical processes we observe on these planets today are probably very similar to those that took place at various locations in the original solar nebula. What are the products of these reactions?

Dr. Smith has already alluded to the probability that these products include organic compounds of interest to us in our attempts to unravel the chemistry that took place prior to the origin of life on Earth. The most obvious evidence we have that such chemistry is actually occurring on Jupiter is the presence of colored regions in the Jovian clouds. Yet we still do not know the identity of the chromophores that produce the colors we see. Organic polymers, polysulfides, and red phosphorous are all likely possibilities.

Perhaps the most famous colored area on Jupiter is the Great Red Spot and we now know from both ground-based and Voyager observations that the atmospheric disturbance responsible for this feature propagates to altitudes that are accessible to UV observations. We do <u>not</u> know what the red material is - Voyager has been unable to tell us and it seems unlikely that the Galileo Project or further ground-based studies will be of much help. With its high spatial and spectral resolution, Space Telescope may at last solve this enigma.

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But that is only the most obvious of many possible studies of the chemistry of the upper atmospheres of the giant planets and their satellites. We already know that a rich variety of photochemical reactions is taking place, but we need much more information on the products of these reactions and their global distribution.

Moving now to a consideration of smaller bodies, I would like to emphasize the special importance of Titan, the largest satellite of Saturn. The atmosphere of this satellite is at least three times as dense as that of Mars, but its composition is still poorly understood. We know it contains a large amount of methane, perhaps over 95%, with small traces of higher hydrocarbons. There is a possibility that a large fraction of the atmosphere is made of a mixture of nitrogen, and neon, with perhaps a detectable amount of carbon monoxide. The latter was a suggestion made by Dr. Robert Danielson, who was the first person to understand that the peculiar thermal emission Titan produces is caused by an inversion in its upper atmosphere.

What makes Titan so interesting is its unusual characteristic of having an evolved, reducing atmosphere. It can lose hydrogen, yet the atmosphere has retained a hydrogen-rich character. This is totally different from the oxidized atmospheres we find on small bodies in the inner solar system. And here again chemical evolution is occurring. We see evidence of this in the photochemical products (C_2H_2, C_2H_4) detected in the upper atmosphere and in the presence of a reddish haze that seems to envelope the entire satellite.

Dr. Caldwell and I have been studying Titan in the UV with the help of the IUE. We find no evidence for a brightness increase with decreasing wavelength consistent with Rayleigh scattering, even at 2200 Å, and we cannot even detect Titan below 2000 Å. With the Space Telescope, we could improve both the wavelength coverage and the spectral resolution, perhaps at last identifying some of the other atmospheric constituents and better characterizing the red aerosol. Once again we want to know what the chemistry taking place in this natural laboratory can tell us about pre-biological chemistry on the primitive Earth.

Our interest in Titan should not distract us from other satellites we presently know much less about. First on the list here is Triton, the large satellite of Neptune. Triton did not appear on Dr. Morrison's illustration of bodies intermediate in size to the moon and Mars, because we don't yet know how big this object is! Space Telescope will give us that answer with one or two images, and will also permit us to substantiate the intriguing possibility that this satellite too has an atmosphere.

In the case of comets, I would only like to emphasize Dr. Morrison's observations concerning the primitive state of these bodies. It seems quite likely that they were the first objects to condense out of the solar nebula. As such, we may expect them to contain frozen remnants of the interstellar medium, in which virtually no chemical processing has taken place. While we cannot expect Space Telescope to tell us much about the interstellar grains that comets may contain, we can expect to learn more about the molecules frozen in comet nuclei, which may be the same molecules that form the ever-growing list compiled by radio astronomers studying dense interstellar clouds. The organic compounds in comets have a special relevance to our larger goals, since they may have given a head start to organic synthesis on the primitive Earth. Even if the compounds themselves did not survive entry into our planet's early atmosphere, cometary impacts may have been an important source of the volatile elements that are essential for the origin of life. We must know much more about the composition of these objects before we can sensibly attempt to recreate our planet's early history. Space Telescope is bound to provide new information through high-resolution studies of cometary spectra at spatial resolutions heretofore unobtainable.

Perhaps the greatest adventure we can take with the ST in our efforts to establish our origins is to look for other solar systems. Science often makes its greatest leaps when it has a number of different examples to classify and compare. It would be wonderful to be able to do that with solar systems - to know which stars have planets and which do not, whether there are systematic differences in the types of planetary systems associated with stars of differing spectral type, etc. But the fact is that while we have some good observational hints and some persuasive theoretical arguments, we presently know of only one solar system in the universe: our own.

Many of us have played the game of trying to calculate the number of advanced civilizations in the galaxy, N, following a straightforward equation established by Frank Drake nearly twenty years ago $N = R_* f_p n_e f_\ell f_i f_c L$. In this expression, R_* is the rate of star formation, f_p is the fraction of stars that have planets, n_e is the number of earth-like planets in each system, f_ℓ is the fraction of such planets on which life develops, f_i is the fraction of such inhabited planets on which intelligent life develope, f_c is the fraction of planets with intelligent life on which a civilization capable of interstellar communication emerges and L is the lifetime of such civilizations.

At the present time, astronomy can only evaluate the first term in the Drake equation. The value of the other factors must be guessed, and the numbers become progressively more speculative as we move to the right. But there is no rule against playing this game with real knowledge, and Space Telescope appears to have the ability to give us our first good estimate of f_p. Two basic techniques are available: astrometric studies of the motions of nearby stars, and direct inspection of stellar images, in which light from the star is blocked internally or by a distant occulting disk (the moon?). If we are very lucky, and find planets in the α Centauri system, we may even be able to estimate n_e. We shall still be forced to extrapolate to other stars in the galaxy, but we should be twice as confident in doing so as we are today.

Brandt: Comet research with the Space Telescope should be profitable in the following areas.

1. Spatial Resolution - The molecular plasma is organized by the magnetic field into rays. Their diameter is presently thought to be $\lesssim 10^3$ km. The ST should resolve the rays or reduce the upper limit to $\sim 10^2$ km.

Synoptic coverage of ray evolution will be most important for ST because ground-based observing conditions make obtaining proper photographic time sequences nearly impossible. The most notable exception in this century was comet Morehouse in 1908. Most photographs provide only snapshots and the situation makes the understanding of cometary morphology, particularly of the plasma, very difficult. A small number of concentrated sequences with the WF/PC should be fundamental. An obvious time for this would be during the 1985-86 apparition of Halley's comet. Coordination of the ST sequences with the prime observing times of the proposed Halley/Tempel 2 Comet Mission would enhance the scientific return.

2. Motions - Patterns with speeds in the range 10 to 200 km s^{-1} have been observed in comet tails. However, their physical origin - waves versus bulk motions - has not been settled. Measurements of doppler shifts from the ST could resolve this issue.

3. Spectroscopic Diagnostics - The spectra of comets, particularly in the ultraviolet, hold great promise. For example, a rocket spectrogram of comet West on March 11, 1976 (obtained by the Laboratory for Astronomy and Solar Physics, NASA/GSFC) shows many species of interest in the range 1600 to 4000 Å. These include CO^+, CN^+, CS, OH, CO_2^+, NH, and CN. High resolution spectra in this range and at shorter wavelengths on new comets should probe physical conditions in the cometary atmosphere through the construction of synthetic spectra. There are also some interesting isotope ratios that can be measured in the ultraviolet (including D/H).

Baum: The search for planets around stars seems destined to be an exciting adventure with high potential for public interest and important implications for the future of space exploration. There are several possible methods for the detection of extra-solar planets. The radial velocity variation of parent stars due to their planets can be pursued fairly well from observatories on the ground. Interferometric methods are also being explored on the ground and may have future potential in space. Direct imaging detection may be barely possible from space, but it puts formidable demands on optical and detector performance. Astrometric detection of the positional variation of parent stars is the method on which I want to focus attention because that is the method of planetary-system detection for which the Space Telescope can play a key role.

Astrometry also has an advantage over the radial velocity approach in that the likelihood of detection is not dependent on the spatial orientation of a planetary system. No matter how a planetary system is oriented, the resulting positional wobble of the star will have roughly the same amplitude, whereas the amplitude of the star's radial velocity variation has a first-order dependence on the orientation of its planetary system.

Astrometry of planetary-system candidates will probably be attempted with the Wide-Field/Planetary Camera, with the Fine Guidance System, and possibly with the Faint Object Camera. At the present state of instrument development, the Wide-Field/Planetary Camera seems to offer the greatest promise. The Fine-Guidance System, which operates astrometrically down to 17th magnitude, utilizes the positional readout of moving parts and would need to preserve long-term reproducibility equivalent to 0.5 micron in the focal plane to achieve the claimed accuracy of 2 milliarcseconds. The Faint Object Camera has a rather small field for finding enough reference stars, and its astrometric reproducibility depends on the stability of electronoptical components.

The Wide-Field/Planetary Camera (WF/PC) can work astrometrically much fainter (22nd mag.) than the Fine-Guidance System but covers a smaller field. The field is imaged either at f/12.9 or at f/30 on to four CCDs. Milliarcsecond astrometry will probably be limited to the quarter field covered by a single CCD, where astrometric reproducibility will depend only on long-term stability of the thermostated silicon membrane of the CCD.

Reaching faint magnitudes with high S/N ratios means that there will usually be an abundance of reference stars within a small angular distance of each program star. Even more important, the irregular motions of faint reference stars (due to their companions) will typically be smaller than the irregular motions of the program star we seek to detect. In the jargon of astrometry, the "cosmic errors" will be acceptably small. For the detection of planetary systems, where milliarcsecond accuracy is needed, this suppression of "cosmic errors" is important.

Each star image produces a mound of charge carriers a few pixels wide on the CCD. Therefore, the determination of the centroid of a star image will be precise if there are enough charge carriers in the image for the statistical uncertainty ($n^{-\frac{1}{2}}$) to be small, if there are enough pixels within the star image to sample its profile adequately, and if the sensitivity profiles of individual pixels are not radically non-uniform.

There is in fact an optimum relationship between the size of a star image and the size of a pixel. If the effective focal length is too short so that the optical image is excessively compressed, the star image profile will occupy too few pixels for its centroid to be well determined. On the other hand, if the effective focal length is too long so that the optical image is excessively magnified, the star image profile will occupy more pixels than necessary for precise centroid determination, while the CCD will cover too small a field in the sky to provide enough reference stars for astrometry. The WF/PC f/30 and f/12.9 systems fall in an optimum range between those two situations.

Figure 1 shows the expected accuracy of astrometry with the CCD cameras as a function of star magnitude for ST exposure times of 1000 seconds. This plot indicates that an accuracy of about 1 milliarc-second should be achieved down to 22nd magnitude with the f/30 camera, whereas the f/12.9 camera has a 2-milliarcsecond error at that magnitude. However, the f/12.9 camera covers a field five times larger in sky area, so more reference stars would be available. Bars at the left-hand ends of the curves in Figure 1 indicate approximate saturation magnitudes for 1000-second exposures. For shorter exposures, these curves (and the saturation magnitudes) march toward the left.

Many of the nearby stars that are astrometrically desirable to test for the presence of planetary systems are bright compared with saturation magnitudes for any reasonable exposure times that provide enough reference stars. These brighter candidates therefore have to be separately attenuated without introducing variable astrometric errors. A suitable attenuation factor (6 or 7 magnitudes) can be produced rather easily at the f/24 focal plane by providing a tiny bare spot (non-aluminized spot) on one face of the pyramid mirror and putting an antireflection coating on it.

How much positional wobble of a candidate star are we looking for, and therefore how many candidates are in reach of the ST instruments? If one plots the actual wobble of the Sun due to the planets of our own Solar System, it is not a simple sine wave with a 12-year period due to Jupiter. It is a surprisingly complex curve in which all the major planets play significant roles. Using solar wobble distant alien observers might detect the existence of a planetary system around our Sun within a few years, but the specific contents of our Solar System would take them many decades to figure out.

Nevertheless, the contribution of Jupiter is a good yardstick for

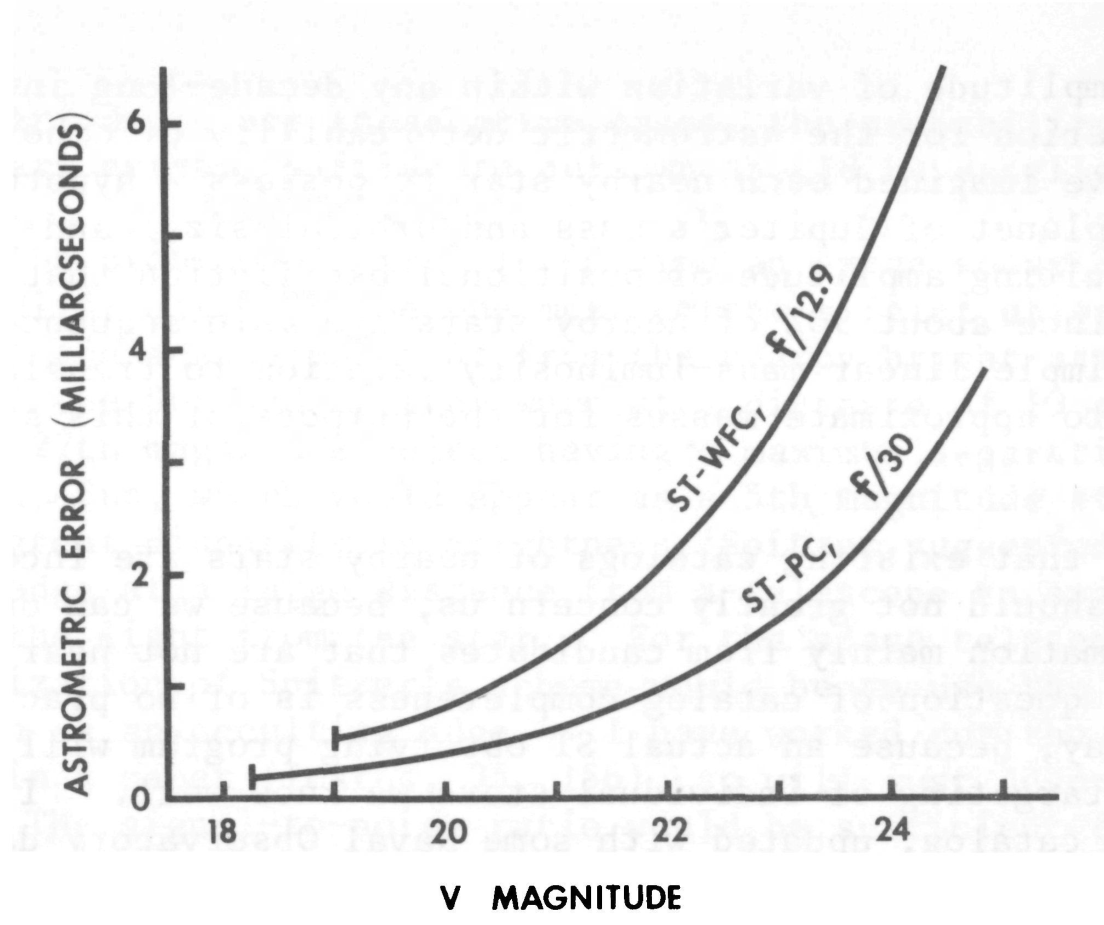

Fig. 1. Theoretical error in the location of the centroid of a star image, plotted as a function of star magnitude, for a single 1000-second ST exposure through a photovisual filter. Bars at the left-hand ends of the curves represent saturation magnitudes (in 1000 seconds) for the f/12.9 and f/30 CCD cameras, respectively.

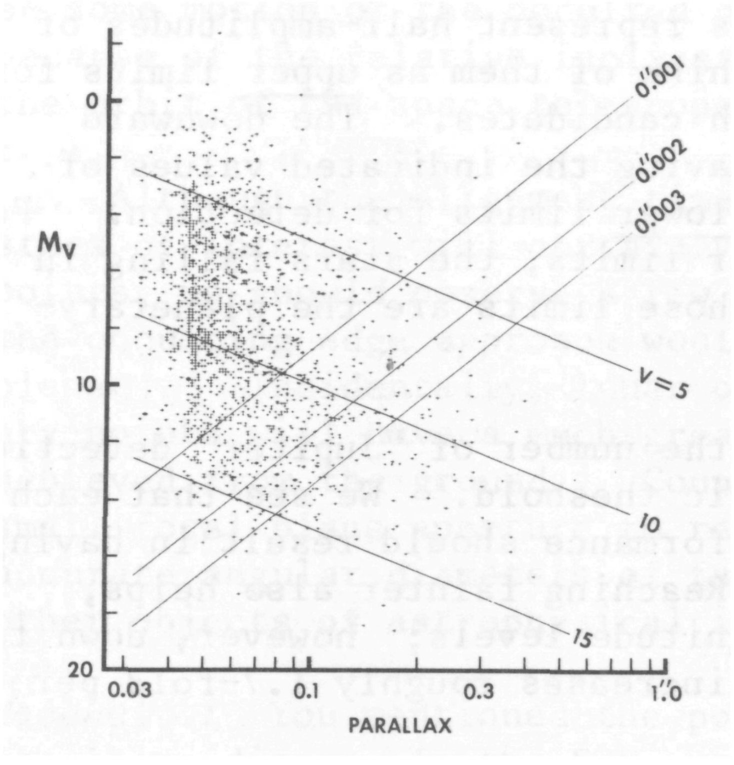

Fig. 2. The absolute magnitude-parallax distribution of nearby stars from Gliese's catalog. Upper and lower limits for the detection of hypothetical "Jupiters" are indicated by the sloping lines, representing possible values for the astrometric accuracy (arcseconds) and V magnitude threshold of an instrument.

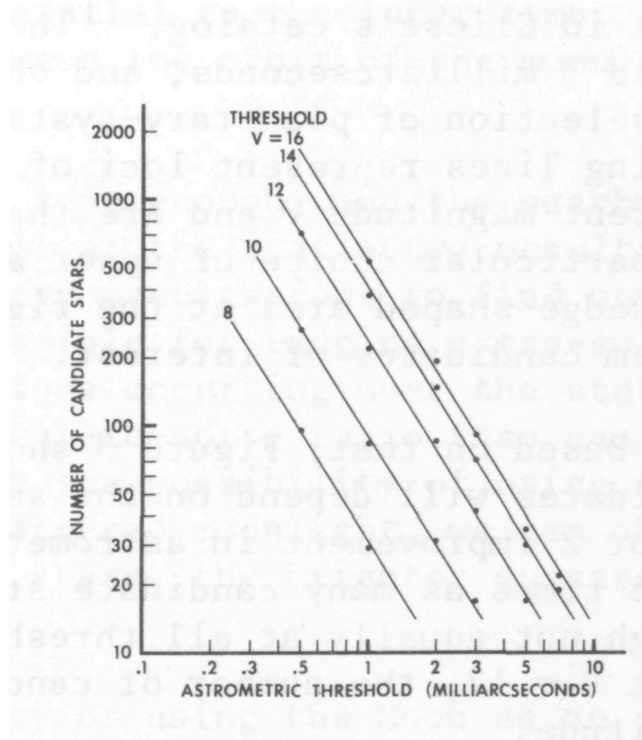

Fig. 3. The number of planetary-system candidates that can be investigated with an instrument of given astrometric accuracy and magnitude threshold. These data are taken from Figure 2 and are based on supposing each star to possess a hypothetical "Jupiter".

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the typical amplitude of variation within any decade-long interval. So, as a criterion for the astrometric detectability of other planetary systems, I have imagined each nearby star to possess a hypothetical "Jupiter" (a planet of Jupiter's mass and orbital size) and have calculated the resulting amplitude of positional oscillation that would be expected. Since about 90% of nearby stars are main-sequence dwarfs, I have used a simple linear mass-luminosity relation to translate absolute magnitudes into approximate masses for the purpose of this statistical exercise.

The fact that existing catalogs of nearby stars are incomplete near their limits should not greatly concern us, because we can draw the desired information mainly from candidates that are not near catalog limits. The question of catalog completeness is of no practical interest anyway, because an actual ST observing program will have to be based on the targeting of individual stars we know well. I chose Gliese's 1969 catalog, updated with some Naval Observatory data, because it was conveniently at hand in machine-readable form. I thank Dr. Westphal and his colleagues at Cal Tech for providing me with a magnetic tape suitable to the present exercise.

The amplitudes of positional oscillation of nearby stars that would be produced by hypothetical Jupiters is represented by the family of upward sloping lines in Figure 2, which is a plot of M_V versus π for stars in Gliese's catalog. These lines represent half-amplitudes of 1, 2, and 3 milliarcseconds, and one may think of them as upper limits for the selection of planetary-system search candidates. The downward sloping lines represent loci of stars having the indicated values of apparent magnitude V and are therefore lower limits for detection. For any particular choice of upper and lower limits, the stars falling in the wedge-shaped area at the right of those limits are the planetary-system candidates of interest.

Based on that, Figure 3 shows how the number of "Jupiter" detection candidates will depend on the astrometric theshold. We see that each factor 2 improvement in astrometric performance should result in having three times as many candidate stars. Reaching fainter also helps, though not equally at all threshold magnitude levels; however, down to about V = 12, the number of candidates increases roughly 1.7-fold per magnitude.

It is evident from Figure 3 that the Space Telescope CCD cameras could choose from among more than 500 candidate stars if they reach a threshold of 1 milliarcsecond. For a more conservative selection, there are about 100 candidates at the 3-milliarcsecond level. And that list might wisely be reduced to about 10 prime cases for early Space Telescope imaging, excluding cases with close stellar companions, with unfavorable distributions of reference stars, or with excessively long

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expected periods. For those prime cases, the probability of detecting any planetary systems similar to our own should be excellent.

Elliot: The problem of directly imaging an extra-solar planet is extremely difficult, because one must detect a faint object in the presence of the scattered light from the nearby bright star. For example, if the Sun and Jupiter were at a distance of 10 pc, Jupiter would be a 27th magnitude object having a maximum separation of 0.5 arcsec from the Sun, which would appear as a 5th magnitude star. To overcome this great disparity in brightness, Spitzer suggested that an occulting edge at a large distance from a telescope in space be used to attenuate the light from the star. For the space telescope, a practical realization of Spitzer's scheme would be to use the black limb of the moon as an occulting edge. I have worked out the details of this plan in a paper (Icarus, 35, 156), so will just describe the main results. The signal-to-noise ratio would be sufficient to detect a Jupiter at 10 pc, but the alignment between the telescope and the lunar limb must be maintained for about 20 minutes. This would be possible for specialized orbits, but not the one presently planned for the Space Telescope. However, twice during each orbit of the Space Telescope, the moon will appear nearly stationary relative to the star fields, so that any object occulted precisely at the stationary point would remain within 0.05 arcsec of the lunar limb for about 9 seconds. There will be some motion of the occulted object parallel to the lunar limb, because of the relative inclination between the orbit of the moon and the orbit of the space telescope.

Although the alignment time is not long enough, and the nearby stars of interest will certainly not fall at the stationary occultation points, we should observe a few stationary occultations to find out if the occulting edge approach would be feasible for imaging extra-solar planets. Incidentally, lunar occultations occurring near the stationary points will have a much greater signal-to-noise ratio than can be achieved from the ground. Coupled with the possibility of using a small focal plane aperture to reject scattered moonlight, we can obtain accurate angular diameters of faint red stars, the brighter quasars and other objects of astrophysical interest.

Macchetto: You mentioned the possibility of using the Moon as an occulting disc. In the FOC, we have a built-in occulting disc which we call a "coronagraphic" mask. With this disc, we can attenuate $\Delta m \approx 19\ m_V$, depending on the angular distance and on the final quality of the optics.

Fastie: I would recommend the investigation of a small number of nearby stars for planetary systems by direct imaging. It looks as though the optics will be very good with wavefront errors less than $\lambda/50$. There is a good chance that the telescope will be diffraction limited at

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3000 Å and correspondingly the Airy disc moves in reducing the Airy continuum which limits the detection of very faint companions.

Hemenway: The Fine Guidance Sensors should not be discounted for the purpose of detecting extra-solar systems planetary systems via astrometric measurements.

Elliot: If the faint object camera has an effective occulting spot and the telescope optics are good, then it might be possible to detect a Jupiter type planet near α Centauri A. Although this star is part of a multiple system, stable planetary orbits would probably be possible close enough to the star. A "Jupiter" orbiting at 5 a.u. from α Centauri A would reach a maximum separation of 4 arcsec from the star and would be 23rd magnitude. This observation should be attempted.

van de Hulst: Some participants have suggested that the Planetary Camera is the best instrument to be used in the search for extra-solar system planets. You will see from the article by Bahcall and O'Dell that the highest angular resolution is obtained with the f/96 mode of the Faint Object Camera which is a factor of two better than the Planetary Camera.

Elliot: As with the study of upper atmospheres, the advantage of using the Space Telescope for observing occultations by rings is the better signal-to-noise ratio. For the Uranus rings we need a high signal-to-noise event to resolve the controversy of whether or not there is material of low optical depth between the nine known rings and to search for new rings. Another goal would be to obtain precise optical depth profiles of the rings. Already, the two most advanced models for the rings - one by Dermott, Gold and Sinclair and the other by Goldreich and Tremaine - are attempting to explain the structure of the ε ring. More accurate data for these structures would further constrain their attempts, and perhaps determine which - if either - of these two models is correct. Since both of these models invoke small satellites to explain the sharp edges of the rings, it would be important to use one of the cameras to search for a possible reservoir of such satellites just outside the ring system. These satellites could be as bright as 17th magnitude, but probably several magnitudes fainter.

We should also use the high angular resolution potential of occultations to probe the rings of Jupiter and Saturn to see if they have narrow structures, akin to the Uranian rings. No photoelectric occultation data for these rings has yet been obtained. Because of its ability to reject background light, the Space Telescope would be the perfect instrument for this work.

Baum: Although I am somewhat more pessimistic than Dr. Fastie about the probable amount of scattered light in the wings of star images

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recorded with Space Telescope cameras, any images of stars that are planetary-system candidates should certainly be scrutinized very closely for any direct evidence of low-mass companions (not necessarily sub-stellar). But in my opinion, the inspection of star images would not alone be a sufficient test for planetary companions, so an organized ST search should instead be based on astrometric detection.