The year 1990 marked the launch of the Hubble Space Telescope (HST) into orbit from the Space Shuttle. *The Astronomical Quarterly* chose to reprint the unpublished report written by Lyman Spitzer as early as 1947, on the benefits to astronomy from space telescopes. Artificial earth satellites launched by rockets were just being talked about then; the first success came in 1957 with the launch of 'Sputnik' by the then USSR. Putting down the science which could be done by space telescopes at such an early juncture reflects great foresight and courage. The founding of NASA in the USA marked the onset of a civilian space programme with much less secrecy, and the funding for the space telescope was finally approved in 1977.

It is noteworthy that the report even indicates the steps towards the final goal and the scientific benefits which would result at each stage. All branches of astronomy are given due space, including the solar system. Here we have a 33 year old professor calmly sketching a roadmap for a field which did not exist, and which many people doubted would ever exist. Spitzer himself encouraged the efforts by his Princeton colleagues- Light, Danielson, and Schwarzschild to work with balloon-borne telescopes. These revealed new features of the Andromeda galaxy core and the Sun's surface. He was deeply involved in 'Copernicus' – a small orbiting telescope with an 80 cm mirror which gave the first glimpse of the ultraviolet sky when it went into orbit. Spitzer lived to witness the launch of Hubble – the journal adds a 'Postscriptum' by the original author. He had proved to be a good astrologer as well!

The X-ray, optical, and ultraviolet telescopes on board India's own ASTROSAT, launched by ISRO in 2016 were designed and built by astronomers, many of whom had worked with smaller satellites and balloons – following the same pattern. Space telescopes will play an increasingly important role in the astronomy of the future.

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ASTRONOMICAL ADVANTAGES OF AN EXTRA-TERRESTRIAL OBSERVATORY

LYMAN SPITZER, Jr. [1]

This study points out, in a very preliminary way, the results that might be expected from astronomical measurements made with a satellite vehicle. The discussion is divided into three parts, corresponding to three different assumptions concerning the amount of instrumentation provided. In the first section it is assumed that no telescope is provided; in the second a 10-inch reflector is assumed; in the third section some of the results obtainable with a large reflecting telescope, many feet in diameter, and revolving about the earth above the terrestrial atmosphere, are briefly sketched.

It should be emphasized that this is only a preliminary survey of the scientific advantages that astronomy might gain from such a development. The many practical problems, which of course require a detailed solution before such a satellite might become possible, are not considered, although some partial mention is made of certain problems of purely astronomical instrumentation. The discussion of the astronomical results is not intended to be complete, and covers only certain salient features. While a more exhaustive analysis would alter some of the details of the present study, it would probably not change the chief conclusion -- that such a scientific tool, if practically feasible, could revolutionize

[1] The report re-printed here appeared as Appendix V of a larger document prepared for the Project RAND of the Douglas Aircraft Co., on 1 September 1946. At that time, Prof. Spitzer was on the astronomy faculty of Yale University; he has been affiliated with the Princeton University Observatory since 1947.

131

astronomical techniques and open up completely new vistas of astronomical research.

I. Solar Spectroscopy with a Small Ultra-Violet Spectroscope

The simplest astronomical instrumentation for a satellite would be a small spectroscope, analyzing the ultra-violet radiation which it receives from any portion of the sky; in practice, this would be the solar spectrum whenever the sun was visible. Such a spectroscope could analyze either the light incident on a diffuse reflector or the light passing through a small LiF sphere, or bead. Such a system has the advantage that it would not need to be accurately oriented in any particular direction. The intensity in the spectrum could presumably be radioed down to earth. An instrument of this sort would have the following uses:

1. Continuous Recording of the Solar Ultra-Violet Spectrum

The scientific and military importance of information on the sun's ultra-violet spectrum has already been pointed out. [2]

Occasional spectra of the sun in the far ultra-violet can presumably be obtained with high altitude rockets which subsequently fall to earth. However, for an adequate picture of the sun's probably large variability in ultra-violet radiation, more frequent measurements may be necessary. For a complete examination of the effect which solar disturbances produce on terrestrial phenomena, especially on conditions in the ionosphere, a relatively continuous portrayal of the sun's output of ultra-violet energy may be required. For example, if a radio fade-out occurs at some particular time, only a record of the solar spectrum during the time immediately preceding can show what the relationship between sun and earth was for that particular fade-out. More important still, for detailed predictions of ionosphere conditions, and thus for practical advance information on radio transmission conditions, daily measurements of the sun's ultra-violet

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[2] Goldberg, L. and L. Spitzer, Jr. 1946, "The Importance of High-Altitude Spectroscopy", Project RAND *Report* (15 July 1946).

spectrum are believed to be essential. These can probably be obtained most simply by a satellite observatory.

2. Detailed Analysis of the Earth's Upper Atmosphere

As seen from the satellite, the sun will rise and set at frequent intervals. On each such occasion, the sun's ultra-violet light will change markedly as the sun's rays shine through atmospheric layers of changing height. By observing changes of the spectrum with time it would be possible to obtain a detailed picture of how the densities of different types of atoms in the earth's upper atmosphere change with changing height. While essentially similar information could be obtained from a rocket which rose out of the earth's atmosphere and then fell back to earth, the observations from a satellite could be obtained much more frequently. In view of the probable variability of the ionosphere, resulting from the variability of the sun's ultra-violet radiation, rather frequent spectrographic observations of the structure of the ionosphere, as well as of the sun's ultra-violet spectrum, are probably required to indicate exactly what is happening. It may well be the case that this information can be obtained at less cost with such a satellite than with a series of rockets of lower velocity.

II. Spectroscopy of the Sun and Stars with a 10-inch Reflecting Telescope

To obtain information about the ultra-violet spectrum of the stars, or to analyze in detail the sun's surface as seen in ultra-violet light, a telescope is required, together with means for orienting the instrument in any desired direction. Orientation might be accomplished in principle by reducing the angular momentum of the satellite to zero by means of external jets; thereafter the satellite could be rotated by internal means to any particular direction, and would point in that direction indefinitely unless hit by a meteorite. Since the telescope would be designed for spectroscopic purposes only, the shape of the mirror would not need to be highly accurate.

A 10-inch reflecting satellite telescope, equipped with one or more spectroscopes, would be a powerful astronomical tool. While it would intercept less light than the large reflecting telescopes on earth, it would have the advantage that the background light from the night sky would be much reduced, provided that the satellite was above the atmospheric layers responsible for this night illumination; 500 miles should be adequate for this purpose. Thus the faintest star which could be reached with such a telescope might be as faint as that which can just be photographed with the 100-inch telescope, provided that photocell techniques can reach the point where they are as effective as the photographic plate. A photon counting technique, with the use of long "exposures" or, more appropriately, "counting intervals" would probably serve this purpose. Such a telescope-spectroscope combination could measure the spectra of stars, planets, etc., down to at least 1000 Å and also out to the infra-red, without the absorption of the earth's atmosphere, which blots out all the ultra-violet and obscures many regions in the infra-red. Listed below are some of the astronomical uses of such an instrument.

It may be noted that practical uses of this instrument would not be immediate; this would be an instrument which might be expected to increase very basically our understanding of what goes on in the stars and in the spaces between them. Since in this way we obtain information on the behavior of matter under conditions not attainable in the laboratory, knowledge of fundamental physics would thereby be enhanced.

1. Detailed Information on Solar Meteorology

With a reflecting telescope and accessory equipment, sunspots, prominences, and other types of storms on the sun could be examined in ultra-violet light of different wavelengths. In particular, the behavior of the resonance line of hydrogen (Lyman[-α]) at 1216 Å would give basic information on the nature of these puzzling and complicated disturbances, which are related to the variability in the output of ultra-violet radiation from the sun.

2. Composition of Planetary Atmospheres

The small amount of O_2 and H_2O present in the atmosphere of Mars and Venus cannot be detected spectroscopically because of the absorption produced by these same molecules in our own atmosphere. A spectroscopic satellite telescope could observe the spectra of planetary atmospheres without any such interferences, and could supplement observations in the infra-red with equally useful ultra-violet data.

3. Structure of Stellar Atmospheres

Among the most abundant elements in typical stars are hydrogen, helium, carbon, nitrogen and oxygen. The absorption lines produced by these atoms in their lowest states (called "resonance lines") all lie in the ultra-violet; the absorption lines of these atoms in the visible spectrum all arise from states whose excitation potential is at least seven volts; since few atoms are so highly excited, the visible absorption lines produced by these atoms are all very weak, except for hydrogen, whose great abundance makes up for its high excitation potential. Thus practically no direct evidence is available on the behavior of helium, carbon, nitrogen, or oxygen in most stars. While the resonance lines of helium lie in the far ultra-violet at about 500 Å, those of carbon, nitrogen and oxygen all lie between 1000 and 2000 Å; the resonance lines of these three elements are unquestionably very strong in the spectra of most stars, and should be readily observable with a satellite spectroscopic telescope. Such observations should indicate any differences in composition between different stars -- these differences are important in stellar evolution and stellar energy generation. In addition, the nature of unusual stellar atmospheres -- expanding, rapidly rotating, etc. -- would be more clearly indicated by information on the behavior of such abundant elements as carbon, nitrogen and oxygen as well as by the behavior of the resonance lines of hydrogen.

4. Color Temperatures of Hot Stars

For stars hotter than about 15,000°C, the color of the star, as measured in visible radiation, is independent of temperature. Measurements in the ultra-violet would help to determine the surface temperatures of hot stars, a basic item in astrophysical research.

5. Bolometric Magnitudes

The determination of the total energy radiated by a star depends on the measurement of the total heat energy reaching the earth from the star; i.e., on the "bolometric magnitude". For stars whose surface temperature is similar to that of the sun, corrections for infra-red and ultra-violet absorption in the earth's atmosphere are not too serious, but for very cool or very hot stars the result depends heavily on the assumed corrections. Bolometric measurements made on a satellite observatory would give bolometric magnitudes directly for stars nearby, unobscured by interstellar dust.

6. Analysis of Eclipsing Binaries

Much of our present information about the masses,radii and structure of stars has been derived from eclipsing binaries. Measurements in the ultra-violet would be a powerful new tool in such research. For example, to determine stellar masses it is necessary to observe the Doppler shifts in the lines produced by each of the two stars, and in this way to measure the velocity of each. When the stars are of unequal luminosity this is difficult. However, the less luminous star is frequently smaller and hotter. In ultra-violet radiation the smaller star will frequently be more luminous, and from a satellite observatory its ultra-violet spectrum could be observed, and its velocity thus determined. Changes in the shape of the light curve during eclipse with changing frequency would also give important information on the structure of the atmosphere and on the nature of the opacity of matter in the stars.

7. Absolute Magnitudes and Stellar Distances

If the surface temperature of a star is approximately known from its spectrum, its absolute magnitude can be found if its radius can be estimated. Since the surface gravity and resulting pressure decrease together with increasing radius, a measurement of pressure suffices to give the absolute magnitude, which in turn gives the distance of the star. Observations of visible stellar spectra have given extremely important results along this line by determining the relative numbers of neutral and ionized atoms, which depend on the pressure. Measurements in the ultra-violet would yield data on the presence of highly ionized atoms, not detectable in visible radiation, and would greatly increase the sensitivity of this method for determining stellar brightnesses and distances.

8. Composition of Interstellar Gas

Interstellar atoms and molecules are known to be present between the stars, and to have a total aggregate mass about equal to that of the stars. Such particles are all in their ground state; hence observations of stellar spectra in the visible give no information on the presence of many of the atoms and molecules that may be expected. Measurements in the ultra-violet would give information on the density of interstellar hydrogen in space near the sun, and would indicate how much if any of this material was in the form of molecules. Such measurements would also indicate how much carbon, nitrogen and oxygen was present. Detailed information on the nature of interstellar gas may be important in understanding the origin of stars and of cosmic rays, which may both be produced from interstellar matter.

9. Properties of Interstellar Absorbing Grains

In addition to atoms and molecules, small grains of matter, about 10^{-5} cm. in diameter, absorb starlight in space. This absorption, generally important only for distant stars, is greater for shorter wavelengths. The distribution of these grains is known to be very uneven. Measurement of stellar spectra in the ultra-violet should therefore provide a very sensitive indication of the presence of these obscuring particles; comparison of this absorption with that in the visible region of the spectrum should yield information about the composition of these particles, which is an important item in the evolution of interstellar matter and in related cosmogonic problems.

10. Nature of Supernovæ

These exploding stars must be the result of some gigantic cataclysm, possibly a chain reaction involving the entire star. The spectrum of the brighter supernovæ is a complete puzzle. Measurements in the ultra-violet would be difficult to obtain with a 10-inch reflector, owing to the great distance and resultant faintness of these objects, but if obtainable might yield an important clue to the nature of the processes involved.

III. Astronomical Research with a Large Reflecting Telescope

The ultimate objective in the instrumentation of an astronomical satellite would be the provision of a large reflecting telescope, equipped with the various measuring devices necessary for different phases of astronomical research. Telescopes on earth have already reached the limit imposed by the irregular fluctuations in atmospheric refraction, giving rise to "bad seeing". It is doubtful whether a telescope larger than 200 inches would offer any appreciable advantage over the 200 inch instrument. Moreover, problems of flexure become very serious in mounting so large an instrument. Both of these limitations disappear in a satellite observatory, and the only limitations on size seem to be the practical ones associated with sending the equipment aloft.

While a large reflecting satellite telescope (possibly 200 to 600 inches in diameter) is some years in the future, it is of interest to explore the possibilities of such an instrument. It would in the first place always have the same resolving power, undisturbed by the terrestrial atmosphere. If the figuring of the mirror could be sufficiently accurate, its resolving power would be enormous, and would make it possible to separate two objects only .01" of arc apart (for a mirror 450 inches in diameter); an object on Mars a mile in radius could be clearly recorded at closest opposition while on the moon an object 50 feet across could be detected with visible radiation. This is at least ten times better than the typical performance of the best terrestrial telescopes. Moreover, in ultra-violet light the theoretical resolving power would of course be considerably greater; ideally an object 10 feet across could be distinguished on the moon with light of 100 Å wavelength. In addition, with such a large light-gathering surface and such low background light, the positions and spectra of stars and galaxies could be analyzed out to much greater distances than is now possible. If the shape of mirror could not be figured so accurately without excessive effort, a large spectroscopic satellite telescope would still have many important uses.

The practical problems of operating such a large installation would of course be enormous. Telemetering back to earth the two-dimensional picture obtainable with such an instrument would involve many problems. With such high angular resolutions, some guiding of the telescope might be necessary to correct for changes in the aberration of light during the satellite's orbit. Absorption and radiation of the light received from both sun and earth would require careful consideration to ensure a constant temperature in the mirror and its mounting (to reduce distortion of the mirror's shape by thermal expansion and contraction) and to give a very low temperature in the photo-electric measuring equipment (to reduce the background of thermal emission from the photo-sensitive surface). To provide for a leisurely orbit and thus for relatively constant conditions, such an observatory should preferably be some distance away from the earth, probably as far as telemetering techniques and celestial mechanics might allow.

Most astronomical problems could be investigated more rapidly and effectively with such a hypothetical instrument than with present equipment. However, there are many problems which could be investigated only with such a large telescope of very high resolving power. A few of these problems are given in the following partial and tentative list. It should be emphasized, however, that the chief contribution of such a radically new and more powerful instrument would be, not to supplement our present ideas of the universe we live in, but rather to uncover new phenomena not yet imagined, and perhaps to modify profoundly our basic concepts of space and time.

1. Extent of the Universe

The 200-inch telescope is designed to push back the frontiers of explored space. It is not likely that this instrument will reach to the greatest distance possible. Further measurements with the more powerful instrument envisaged here would help answer the questions whether space is curved, whether the Universe is finite or infinite. This instrument would help in particular to resolve individual stars in a distant galaxy and to analyze their spectra, thus identifying particular stars of known absolute magnitude and in this way determining accurately the distance to the galaxy. At present the distances of most galaxies are known only very approximately.

2. Structure of Galaxies

With such great resolving power, such an instrument could explore the details of the structure of galaxies, individual stars could be resolved, and the nature of the as yet enigmatic spiral arms could be investigated. Measurement of radial velocities by spectral analysis would yield velocities of rotation in a number of galaxies and thus provide direct information about their masses -- information now available for only a few galaxies.

3. Structure of Globular Clusters

These objects contain so many stars that resolution of individual stars has been possible only for the brighter members. With such great resolving power a much greater percentage of the individual stars could be resolved, some spectra and radial velocities obtained, and a serious attempt made to explore the structure of these stellar aggregations.

4. Nature of Other Planets

The controversy as to the presence of intelligent life on Mars could perhaps be settled by measurements with such a giant telescope. Similarly the type of surface detail present on the other planets could be accurately explored with such high resolving power and invariably "perfect seeing".

POSTSCRIPTUM, May 1990

LYMAN SPITZER, Jr.

In some ways, the most important aspect of this early work is its unstated assumption that large, complex instruments in orbit around the Earth would become a practical possibility within a few decades. In 1945 this point of view seemed very far-fetched to most astronomers. Once this assumption is accepted, the detailed listing of suitable scientific programs for space telescopes became a relatively straightforward task, which I undertook with enthusiasm and pleasure. The resultant survey, printed in 1946, lists many of the scientific programs pursued and planned in optical space astronomy, including the Hubble Space Telescope. Since the limiting effects of the Earth's atmosphere on astronomical research are well known, various items of my list have of course been suggested independently by many other scientists.

Since this 1946 paper did not appear in the astronomical literature and was not generally distributed in reprint form, its direct influence on other astronomers must have been almost negligible. Its chief effect was on me. My studies convinced me that a large space telescope would revolutionize astronomy and might well be launched in my lifetime. When I moved to Princeton in 1947, as Director of the Princeton University Observatory, a program leading toward such a powerful instrument became a long-range goal. This program, which got into high gear after the 1957 launch of the USSR *Sputnik*, included scientific research with a variety of smaller instruments (1982, 1989). Also included were engineering studies (1960), and the development of the SEC Vidicon for use as an imaging detector in space telescopes.

Shortly after the NASA/National Academy summer study group in Woods Hole in 1965, I became chairman of an *ad hoc* committee to study the scientific possibilities of a large space telescope. The chief task of this committee was to prepare a list of important astronomical programs that such a telescope could carry out. Our report (1969) was a greatly expanded version of my 1946 paper. During the work on this report, possible astronomical observing programs were discussed in detail with various groups of astronomers, who in the course of these discussions generally became enthusiastic supporters of such a large and powerful telescope. This support was a major element in Congressional approval (1979, 1989) of the large telescope project in 1977. The existence of the SEC Vidicon as a practical, tested device was also an important element, since in the absence of a suitable detector the formal start of the large space telescope would not likely have been proposed to Congress by NASA.

Through these indirect channels, the 1946 paper has apparently had an appreciable influence on the Hubble Space Telescope program. Now that this instrument is operating in orbit we can look forward to data needed for the well-recognized astronomical problems. To quote my early paper, it is also possible that the Hubble Telescope will "... uncover new phenomena not yet imagined and perhaps modify our basic concepts of space and time."

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