

SOME ASTRONOMICAL CHALLENGES FOR THE TWENTY-FIRST CENTURY

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This paper addresses some of the scientific puzzles that astronomers may face in the next century. Four areas in astronomy are discussed in detail. These include cosmology and galaxy formation, active galaxies and quasars, supernovae and stellar remnants, and the formation of stars and planets. A variety of observatories on the Moon are proposed to attack these astronomical challenges.

INTRODUCTION

It is now fairly well established that the Moon is an excellent location from which to perform astronomical observations (e.g., Burns and Mendell, 1988; Burns *et al.*, 1990). The sky is dark and quiet, especially on the lunar farside. There is very little atmosphere, both in terms of neutral (10^5 molecules/cm³; Taylor *et al.*, 1988) and ionized (<100 ions/cm³; Douglas and Smith, 1985) gases. The ground is stable since the Moon is geologically inactive (seismic energy is 10^{-8} that of the Earth). The backgrounds of light, radio waves, radioactive-induced radiation, and even 1-GeV to 10-Tev neutrinos (Cherry and Lande, 1985) are much less than that on the Earth.

These characteristics have stimulated proposals for a wide variety of astronomical observatories on the Moon (e.g., Mendell, 1985; Burns and Mendell, 1988). Interferometric arrays at radio, optical, and infrared wavelengths will take advantage of the phase coherency that is possible without an atmosphere and on a stable surface. The lower gravity of the Moon may prompt the construction of very large radio dish antennas at high frequencies and large mirror arrays for use in the optical and infrared. The low radiation backgrounds, high vacuum, and negligible magnetic fields may permit the deployment of large-area, sensitive detectors of X-rays, gamma-rays, and cosmic rays, as well as detectors for neutrinos at moderate energies.

Clearly, a discussion of astronomical observatories on the Moon in the 21st century must be motivated by exciting and challenging scientific goals. In this paper, I attempt to examine what some of the astronomical challenges for the 21st century may be. My list is by no means exhaustive, but represents some of my own scientific biases and some of the astronomical programs that I find particularly attractive. My colleagues will surely extend this list. Crystal ball gazing is always dangerous in a field that is as rapidly advancing as astronomy. Such predictions are particularly dangerous now before the Hubble Space Telescope is in full operation and before the launch of the Gamma-Ray observatory, since these remarkable facilities will probably uncover new and interesting problems that could be appropriate for study with telescopes on the Moon. Nonetheless, it is likely that within the four areas that I discuss below a wide variety of interesting problems will remain well into the twenty-first century.

My approach in this paper will be to examine possible astronomical programs for the next century, independent of the location from which the observations will be conducted. In the final section, I will note what types of lunar observatories may contribute to the proposed astronomical programs.

COSMOLOGY AND GALAXY FORMATION

The Hubble Parameter

Hubble discovered in 1929 that the universe expands at a rate that is directly proportional to the distance. The constant of proportionality is now known as the Hubble parameter, H_0 . After nearly 60 years of effort, we still only know the value of this most important cosmological parameter to within a factor of 2 (50-100 km/sec/Mpc). High-resolution, high-sensitivity observations in both the optical and infrared (IR) of "standard candles" such as Cepheid variables and supernovae in distant galaxies are needed to determine accurate distances. These data, combined with spectroscopically measured recession velocities, are used to calibrate the rate of universal expansion. Although the Hubble Space Telescope will make a giant leap forward toward determining the value of H_0 , its aperture is relatively small (2.4 m) and the light-gathering power is limited. A larger optical telescope, possibly on the Moon (e.g., Bely *et al.*, 1989), would be able to resolve Cepheids and supernovae in more distant galaxies, and would possess greater sensitivity because of the larger aperture and lower light background (both galactic and extragalactic). This would also permit the use of fainter variables such as RR Lyrae stars to calibrate the Hubble flow.

Another intriguing possibility for constraining H_0 is the use of water vapor masers in other galaxies. Recently, VLBI observations of trigonometric parallaxes of galactic H₂O masers were used to make the best estimate of the distance to the Galactic Center to date. An ultralong baseline radio interferometer with space-based antennas would be able to resolve masers in other galaxies and thus use similar techniques to determine accurate distances.

We should also conduct searches for other standard candles. An interesting possibility involves X-ray binaries whose periodicities are proportional to their luminosities. An array of X-ray variability monitoring telescopes with modest resolution would be adequate for this task.

Photometry of extragalactic star clusters with a large optical/IR telescope could provide another important distance indicator. Using the classic technique of main sequence fitting to the H-R diagram of a star cluster would allow accurate distance determinations.

Expansion of extragalactic supernovae and supernova remnants offers intriguing possibilities as measured by high-resolution optical and radio interferometers. The proper motion of compact components in the expanding nebulae combined with spectroscopic measurements of the radial velocities can yield a parallax or distance estimate.

More effort should be devoted to combining data from several wavelength bands to determine H_0 . For example, sensitive microwave observations (away from sources of interference and high terrestrial background levels from the sky and ground) of clusters of galaxies coupled with X-ray measurements can, in principle, yield a measure of the Hubble parameter using the Sunyaev-Zeldovich effect (i.e., the cosmic microwave background is diminished by Compton scattering off thermal electrons in the intracluster medium).

Dark Matter and Closure of the Universe

One of the most important realizations of the past few decades is that the majority of matter in the universe (possibly 90%) is nonluminous. The nature of this dark matter is highly uncertain. Candidates include Jupiter-like planets, brown dwarfs, small black holes, as well as weakly interacting particles such as massive neutrinos (hot dark matter) and gravitinos (cold dark matter). The density of dark matter is of critical importance in determining the rate of deceleration of the expansion of the universe and the geometry of spacetime (an open or closed universe).

Galaxy rotation curves have been important in constraining the mass of galaxy halos. The discovery of flattened rotation curves (i.e., nearly constant velocities at large distances from the galaxy core) implies the existence of massive dark halos. Because of the sensitivity requirements, only a relatively few nearby galaxies have been measured. There is a great need to determine rotation curves for more distant galaxies, younger galaxies, and a broader class of galaxies. In addition to the usual techniques involving H-alpha and 21-cm spectral line observations, millimeter and submillimeter telescopes, free of absorption and scattering in the terrestrial atmosphere, could use molecular line transitions for the galaxy dynamics studies.

On larger scales, it has been known since the 1930s that clusters of galaxies must possess significant quantities of dark matter to counteract the large observed velocity dispersions. The magnitude of the motions of galaxies in clusters depends upon the total cluster mass. However, a direct determination of the mass is complicated by uncertainties in galaxy orbits and the state of cluster relaxation. Only relatively nearby clusters have measured dispersions so we presently do not know how cluster dynamics (and thus relaxation) evolves with time. Larger, more sensitive telescopes at optical and radio (HI line) frequencies are needed to make these measurements. However, better constraints on dark matter will come from combining the galaxy velocity data with high spectral and spatial X-ray observations of clusters. Hot gas (10^7 to 10^8 K) between cluster galaxies emits thermal bremsstrahlung radiation and serves as an excellent tracer of the gravitational potential well of the cluster. X-ray line emission can also be used to constrain mass loss from galaxies and motions

of the intracluster medium. This combination of multiwavelength observations could be a useful tool in constraining the nature and extent of dark matter in clusters.

Even larger structures, superclusters and cosmic voids, are powerful probes of dark matter when combined with theoretical models. We need to measure the three-dimensional structure of the universe on scales of hundreds of Mpc at large look-back times. The galaxy covariance function, the distribution of galaxies, and the recently discovered large-scale streaming motions are presently the best tools that we have for distinguishing between various models of galaxy formation (pancake collapse on large scales vs. a hybrid hierarchical clustering). In turn, these models depend upon the particular form of dark matter that forms the seed density perturbation.

Finally, gravitational lenses offer an interesting method to probe dark matter. Multiply imaged quasars at radio and optical wavelengths and time variability of the images can constrain the total mass of the foreground lensing galaxy. However, ground-based studies have been limited by both resolution and sensitivity. Our present inability to detect and distinguish all images formed by a gravitational lens means that the resulting lensing mass estimate will be highly model-dependent.

Evolution of Galaxies and Clusters

An understanding of the formation and evolution of galaxies requires observations of galaxies at large distances. As in the above, ground-based observations have been limited by wavelength coverage (optical through near infrared), resolution, and sensitivity.

In particular, exciting new results using recently developed two-dimensional infrared imaging detectors suggest that primordial galaxies can be observed. Since these galaxies tend to be very red in color, one would like to search for such objects at even longer infrared wavelengths (10 to 100 μm). Large-area, infrared detectors are needed for very deep surveys of galaxies in formation.

High-sensitivity, high-resolution telescopes in the UV, optical, and IR offer the possibility of studying the initial mass function (IMF) of stars in galaxies and extragalactic star clusters. These observations, coupled with submillimeter studies of star-forming regions in other galaxies, will provide a broader perspective on the physics of protostellar collapse and early stages of star formation than is possible using the Milky Way alone.

The detection and imaging of distant galaxy clusters ($z > 2-3$) at both X-ray and optical wavelengths would add greatly to our understanding of the evolution of galaxy environments. In particular, line observations at X-ray energies of cosmologically distant clusters would help us to determine the origin of the elements in the intracluster medium and the evolution of the gas.

Another crucial database that is needed concerns the morphology of younger galaxies. When and how do galaxy disks form? How common is starburst activity and how might this be related to quasar activity? How does the interstellar medium in galaxies evolve with time? These questions could potentially be addressed with telescopes in space or on the Moon at UV, optical, IR, and millimeter/submillimeter wavelengths.

Background Radiations

The 3-K microwave background holds one of the important keys to understanding how structure emerged from the high-energy soup of the early universe. In particular, anisotropies in

this background are directly related to the spectrum of initial density fluctuations (unless an epoch of reionization occurred). Ground-based and balloon observations are difficult because of the Earth's atmosphere. The COBE satellite is the first U.S. spacecraft to be devoted to measurements of the microwave background. However, it too is limited in sensitivity and resolution. One needs to employ a wide range of sensitive detectors from millimeter to the IR at a variety of angular resolutions to detect and measure the full spectrum of anisotropies.

A diffuse X-ray background has been known to exist for nearly two decades. The origin remains unclear. *Einstein* Observatory deep field observations suggested that some of this background is composed of quasars, galaxy clusters, active galaxies, and stars. However, the results are still controversial. A deeper, higher resolution survey over a wide energy range (1 to 100 keV) is needed to resolve this question.

ACTIVE GALAXIES AND QUASARS

Nature of the Engine

Active galaxies and quasars often emit more energy as nonthermal radiation than the superposition of thermal emission from all the stars in the parent object. What kind of "engine" is capable of such energy production? Theoretically, collapsed objects—particularly black holes—seem to have the best promise. Energy can be efficiently extracted from the deep gravitational potential well within an accretion disk. However, there is at present no observational proof that massive black holes exist at galaxy cores.

Several galaxies such as M87 and M32 have suggestions that black holes may be present in their cores based upon studies of the distribution of light and stellar velocities. However, all such arguments are limited by the inability of current instruments to resolve the cores of generally distant active galaxies. An optical/IR interferometer could directly attack this problem with angular resolutions of a microarcsecond.

Similarly high resolutions could be achieved by a space-based radio interferometer. One could study how energy is extracted from the cores, and thus infer the properties of the engine, by observing radio jets at very high resolutions. However, such studies may be limited in linear resolution by Compton scattering effects.

One would also like to observe the gas in the direct environs of the engine. To accomplish this, high-spatial and-spectral resolution images are needed of the narrow-line region surrounding the active galactic nucleus.

Another clue to the nature of the engine can come from variability of the X-ray emissions from AGNs. Such observations set the firmest limits on the size of the emitting region. They also can produce estimates of accretion rates and information on the physics of the radiation processes. Time-serial, ungapped data is needed to detect multiple-periodic structures.

The recent detection of neutrinos from the supernova in the Large Magellanic Cloud ushered in a new observational branch of astronomy. The Moon is a particularly good location for observing neutrinos in the energy range from 1 GeV to 10 TeV since the background is much lower than on Earth. A large area neutrino detector might then be used for observations of active galactic nuclei. The neutrinos are created via high-energy interactions within the accretion disk and travel outward nearly

unimpeded by the intervening galaxies and intergalactic gas. Thus, one may have an opportunity to study particle emissions in the direct environs of the engine and therefore constrain the nature of the engine.

Acceleration of Particles

We still have a very poor understanding of how electrons (and presumably protons) are accelerated to relativistic energies, thus radiating synchrotron emission in both galaxy cores and in larger-scale radio lobes. This is a general question that also applies to the formation of cosmic rays in galaxies, energetic particles in supernovae, and flares on stars and the sun. A very low frequency array (0.5 to 30 MHz) operating on the lunar farside or in lunar orbit offers the best hope for studying such processes. Such observations are not possible from the ground because of man-made interference and the ionosphere, and are difficult from Earth orbit because of the leaky ionosphere and auroral kilometric radiations from the magnetosphere. Low-frequency emission comes from low-energy particles. Broad-band, low-frequency spectra can provide important constraints on particle lifetimes and electron reacceleration. One can potentially differentiate between competing models by examining the shape of the broad-band continuum spectrum at low frequencies.

Higher-frequency observations at IR, optical, and X-ray can also constrain *in situ* particle acceleration in extended jets and lobes by examining the high-frequency turnover in the synchrotron spectrum. However, higher resolutions and higher sensitivities are needed to map these weak emissions.

Quasar-Galaxy Relationship

The nature of quasars remains controversial nearly 30 years after their discovery. There is good evidence for halos around the point-like cores of some nearby quasars; however, one can still argue that these nearby (generally lower-power) objects are not true quasars but are closer to Seyfert galaxies. To resolve this issue, two key observations are needed. First, detection, imaging, and spectroscopy of optical/IR "fuzz" around distant quasars ($z > 2$) are needed. This will require large-aperture telescopes and/or an optical interferometer. Second, one needs to search for galaxies around quasars. A convincing case has been made that nearby quasars tend to occur within groups of galaxies, but similar observations are needed for the more distant quasars.

Quasar Absorption Lines

Lunar or space-based observatories offer major advantages over ground-based facilities in studying quasar absorption lines. Many of the strong resonance lines for low atomic weight gases occur at UV wavelengths. Such strong lines can be used to study the nature of the foreground intergalactic medium, gas in cosmic voids, and spatial correlations of absorption clouds. All these have important cosmological significance. Similarly, quasars that lie in projection near the halos of galaxies or behind clusters of galaxies can be used as tracers of the foreground gas. In particular, the absorption lines could be used to study chemical abundances in galaxy halos and clusters of galaxies. Finally, the strong resonance lines of He and D that occur in the UV will allow us to make direct measurements of the He/H and D/H ratios, thus constraining models of cosmic nucleosynthesis following the Big Bang.

SUPERNOVAE AND STELLAR REMNANTS

Detection of Supernovae in Other Galaxies

Major questions concerning the origin and evolution of supernovae can be studied most successfully by examining supernovae and their remnants in other galaxies. This is an important issue for understanding the evolution of massive stars in galaxies, heat sources in the interstellar medium, and galaxy winds, and has additional possible cosmological significance (re-ionization of the microwave background?). An automated search for such supernovae using large-aperture optical and UV telescopes is required.

As mentioned earlier, supernovae (particularly type I) can be used as important standard candles for cosmological distance determinations and measurements of the deceleration of the Hubble expansion. The dispersion in magnitudes of SNI are small and thus serve this purpose very well.

Nearby Supernovae and Their Remnants

The recent supernova in the Large Magellanic Cloud has demonstrated how successful current models are for describing the evolution of the explosive event. However, one among many surprises that emerged from the data had to do with the progenitor star. Its color and spectral type were quite unlike that expected to produce a type I supernova. Clearly, there is much to be learned about which stars become SNI and SNII. Surveys in both our galaxy and in our neighboring galaxies are needed to fill in missing pieces of the puzzle regarding the final explosive stages of stellar evolution. Since massive stars that produce supernovae radiate most effectively in the UV, space-based studies of such stars would be productive.

Now that the neutrino window is open, neutrino observatories could play a useful role in astrophysics. Neutrino emissions from supernovae are critical tests of explosive nucleosynthesis. High time resolutions over a broad range of energies are needed to constrain models. For more distant galaxies, sensitivity, and thus large-area detectors, will be required.

Much progress has been made in studying the remnants of past supernova explosions. Particularly important advances have come in combining data from radio through X-ray wavelengths. Such a multifrequency approach would be very productive in studying the physics of expanding remnants. High-spectral and -spatial resolution mapping at X-ray, optical, and UV wavelengths are crucial in studying the interaction of the supernova shock wave and the interstellar medium.

Searches for more remnants need to be conducted within our galaxy and within neighboring galaxies. With the several dozen reliable remnant identifications that are presently known, it is difficult to classify supernovae and determine the physics of the progenitor event.

Stellar Remnants

What are the progenitors of various endpoints in the stellar evolution cycle: white dwarfs, brown dwarfs, neutron stars, and black holes? Theoretically, the ideas regarding the evolution of giant stars into compact objects are fairly well established. However, observational verifications are still lacking and there are uncertainties in the details of the evolution. Searches for more of these stellar endpoints are needed. For example, the cooling of a white dwarf is an important check on the equation of state and thermal conduction models. As the star cools, more sensitive

observations at progressively redder wavelengths are needed. Similarly, X-ray pulsations can be used to identify more candidate neutron stars.

In general, X-ray observations are useful probes of the direct environs of stellar remnants. Higher-sensitivity X-ray observations for point sources will push the detectability for remnants radiating with a blackbody spectrum (i.e., accretion disks). Variability studies, as noted above, can set limits on source sizes and accretion rates. X-ray binaries are particularly interesting to study in this regard.

Finally, the cores of globular clusters may house a variety of stellar remnants. High-resolution observations at optical and IR wavelengths can be used to determine the core stellar dynamics and set limits on the masses of compact objects. X-ray observations can provide good hunting grounds for binaries and central compact objects in globular clusters.

FORMATION OF STARS AND PLANETS

Gas Clouds into Stars

One of the shining successes of modern astrophysics has been the theoretical understanding of the evolution of stars on the H-R diagram. Although the "middle-age" portion of a star's evolution is relatively well understood, there remain many unsolved problems regarding the initial collapse and formation of stars from gas clouds.

We have, at present, a poor understanding of the initial mass function (IMF) for stars, particularly for low-mass stars. How does this function depend upon the star's metallicity and location within the galaxy? What is the time dependence of the IMF? How does this function vary with local physical conditions? The answers to these questions, especially for lower-mass stars, will come with detailed imaging and spectroscopic observations in the red and infrared.

The contraction phase of stars from gas clouds is not well understood. For single stars, how is angular momentum from an initially rotating cloud dissipated? What is the role of magnetic fields in the collapse process? The study of these crucial questions will require high-resolution total intensity and polarization observations in the IR. The IR is important to see through the outer cloud and accurately locate the protostellar core. Large-area detectors would provide such sensitive, high-resolution observations. One would like to conduct time-dependent imagery of the cloud cores to examine proper motions and radial velocities of the gas motions. This would require both high-spatial and -spectral resolutions.

Young stellar objects have recently been observed to possess outflows presumably from the vicinity of an accretion disk. The energization and collimation of such flows are uncertain. Observations at submillimeter wavelengths would be most useful here since molecular transitions become optically thin at these wavelengths. One could attempt to study the chemistry of the outflow and direct environs of the protostar as a function of distance from the core. Near-IR and millimeter imaging could be used to determine the location of the core and the properties of the initially collimated outflow.

Little is known about the very earliest stages of collapse of cold clouds. Because of the low temperatures (about 10 K), observations in the far IR would be needed to probe these clouds. The IRAS demonstrated the value of far-IR observations in studying star-formation regions. Two-dimensional polarimetry would be important to examine how magnetic fields support the clouds,

generate turbulence, dissipate angular momentum, and aid in the collimation of outflows. Very little work has been done to date to study these quiescent clouds because of the inaccessibility of the far IR from the ground.

One must also study star formation in other galaxies as a link to understanding the physics of star formation in the Milky Way. Protostellar clouds in our galaxy provide us with an opportunity to study details of the star formation process because of their proximity. Star forming regions in other galaxies provide us with an opportunity to study the broader dependences of star formation on galaxy environment—a more global perspective.

Other Planetary Systems

The formation of planets is even less well understood than stars. Presently, we know of only one planetary system, namely our own. Clearly, searches for other such systems are needed to guide our understanding of our solar system.

One technique that has been suggested for such searches is coronagraphic imaging. The Hubble Space Telescope will conduct this type of imaging for nearby stars. One would like to extend this to more distant and less luminous stars at optical and IR wavelengths using larger lunar telescopes.

The IRAS operating in the far IR revealed several interesting candidates for protoplanetary disks. These observations demonstrate the feasibility of such studies at both IR and optical (using scattered light) wavelengths.

Astrometry of stars is the most straightforward method for detecting gravitational perturbations by planets. Ground-based observations have been conducted for several decades, but with no clear detections because of atmospheric limitations. Optical/IR and radio interferometers with microarcsecond resolution would clearly advance these searches.

POSSIBLE LUNAR OBSERVATORIES

In my opinion, the natural location for the next generation of space-based astronomical facilities, following the Great Observatory series, is the Moon. The many advantages of the Moon described in the Introduction, coupled with the regular transportation, mining, and self-sufficient habitats that are anticipated for the early twenty-first century make lunar observatories look very attractive. In addition, the cost (in fuel mass calculated for shuttle-class engines) of transportation of materials from the Earth's surface to the Moon's surface is only about 50% more than from the Earth to geosynchronous orbit (e.g., Keaton, 1985).

The Moon as a site for astronomy can contribute to an understanding of the astronomical problems described in the previous sections. Among the possible lunar observatories are (1) a farside low-frequency array, operating from about 0.5 to 30 MHz, that would open an entirely new window to the electromagnetic spectrum and contribute to our understanding of particle acceleration from the sun to extragalactic radio sources; (2) an optical/IR interferometer with a resolution of a microarc-

second that could be used to further constrain the Hubble parameter, locate planets around other stars, and resolve the cores of active galaxies; (3) a far-infrared telescope, possibly located within a polar crater, that could take advantage of the natural cryogenic environment of the Moon (with large-area, "naked" detectors) to map stars and galaxies in the process of formation; (4) a submillimeter array, free of the absorption of the Earth's atmosphere and on the stable lunar surface, that could probe deeply into the cool interiors of molecular clouds and measure the dynamics of molecular gas in other galaxies; and (5) a large area X-ray detector that could accurately measure the X-ray background and monitor the variability of compact galactic and extragalactic sources. For more details on these instruments, see Burns and Mendell (1988).

There are many challenges awaiting the astronomical community in the next century. Access to electromagnetic windows in the IR, the UV, submillimeter, X-ray, and very low radio frequencies will allow us to approach solutions to problems from star to galaxy formation. My scope in this paper has been limited. I have not even touched upon exciting problems in solar and planetary astrophysics. However, it is clear that there is an abundance of interesting problems that might be addressed with astronomical observatories on the Moon.

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