Infrared Astronomy After IRAS

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The 250,000 sources in the recently issued Infrared Astronomy Satellite (IRAS) all-sky infrared catalog are a challenge to astronomy. Many of these sources will be studied with existing and planned ground-based and airborne telescopes, but many others can no longer even be detected now that IRAS has ceased to operate. As anticipated by advisory panels of the National Academy of Sciences for a decade, study of the IRAS sources will require the Space Infrared Telescope Facility (SIRTF), a cooled, pointed telescope in space. This instrument may be the key to our understanding of cosmic birth—the formation of planets, stars, galaxies, active galactic nuclei, and quasars. Compared with IRAS and existing telescopes, SIRTF's power derives from a thousandfold gain in sensitivity over five octaves of the spectrum.

THOMAS ALVA EDISON INVENTED A SENSITIVE INFRARED detector and used it to observe the solar eclipse of 1878 from a hen house in Rawlins, Wyoming Territory (*1*). Sir William Herschel (*2*) had discovered the infrared when he measured temperatures in the spectrum of the sun and found that there was energy beyond the red. Lord Rosse (*3*) had detected infrared from the moon. But it was Edison who demonstrated and calibrated his apparatus on the bright star Arcturus and spoke of mapping the whole sky in search of invisible stars, establishing his claim as the first infrared astronomer to look beyond the solar system. Edison's exploits were covered extensively in contemporary newspapers but were quickly forgotten as astronomers concentrated on building and using large optical telescopes. Not until the 1950's and 1960's did advances in low-temperature physics and thermometry and military interest in infrared detection converge to revive the field, particularly in the United States. This revival culminated in the development of the Infrared Astronomy Satellite (IRAS) by the United States, the Netherlands, and Great Britain. After its launch in January 1983, IRAS completed the first deep all-sky infrared survey (*4*). The interest in this survey derives from the unique and important astronomical perspectives provided by the infrared.

Infrared astronomy reveals cool states of matter—solids and molecules. Various mechanisms heat cosmic solids to temperatures between 3 K (*5*) (determined by equilibrium with the cosmic background radiation) and 1500 K (above which most solids evaporate). Over this temperature range, most of the radiated energy lies in the infrared. The bulk of strong molecular spectral lines also lies in the infrared. Cosmic solids and molecules are of special importance in the study of such low-temperature environments as regions of star formation, planetary surfaces and atmospheres, and sites where the first steps toward life may be occurring.

Infrared astronomy explores the hidden universe. Cosmic dust particles are very effective at obscuring parts of the visible universe. The screen of submicrometer-sized grains toward our galactic nucleus is equivalent in projected thickness to a single sheet of paper, yet it extinguishes visible radiation by a factor of 10^{12}. Dense molecular clouds where stars and planets form are even more heavily obscured. Because even these amounts of dust are nearly transparent at wavelengths beyond 3 μm (*6*), infrared astronomers can probe such regions. Frequently, the visible radiation absorbed by dust and reradiated in the infrared accounts for virtually the entire luminosity of dust-embedded stars, active galactic nuclei, and even whole galaxies.

Infrared astronomy also reaches back to the early life of the cosmos. Because of the travel time of light, objects seen now at the greatest distances are young on a cosmological scale. Expansion of the universe produces the cosmic redshift, such that the visible and ultraviolet radiation from familiar objects is constantly shifted with increasing distance toward the red end of the spectrum. The most distant galaxies formed so long ago that the peak of the spectra emitted in their earliest phases has now shifted to 10 μm or beyond. The rich optical emission line spectra of young quasars are also shifted into the infrared.

The Infrared Region and the Goals of Astronomy

Periodically, the National Academy of Sciences (NAS) commissions a high-level committee to reconsider the goals of astronomy and to set a course to achieve them. The most recent study, commonly known as the Field Report (*7*), sets as goals (i) understanding the formation of planets and of the solar system, including the conditions for life in the universe; (ii) studying the formation of stars and their subsequent evolution; (iii) exploring solar and stellar activity; (iv) probing the earliest stages of the universe to learn how galaxies form and evolve to their current state; and (v) learning more about cosmic energy sources, including active galaxies and quasars. Although these goals demand observations from radio waves to gamma rays, the unique infrared perspectives will be essential.

To gain these perspectives, we must utilize dramatic advances in large arrays of detectors, the cooled telescope technology demonstrated by IRAS, and the possibility for Space Shuttle or Space Station to service and extend the lifetimes of orbiting facilities. These elements are combined in the Space Infrared Telescope Facility (SIRTF). SIRTF will be at least 1000 times more sensitive than IRAS.

Most important, SIRTF will be a true observatory with a versatile group of instruments, including (i) a wide-field, high-

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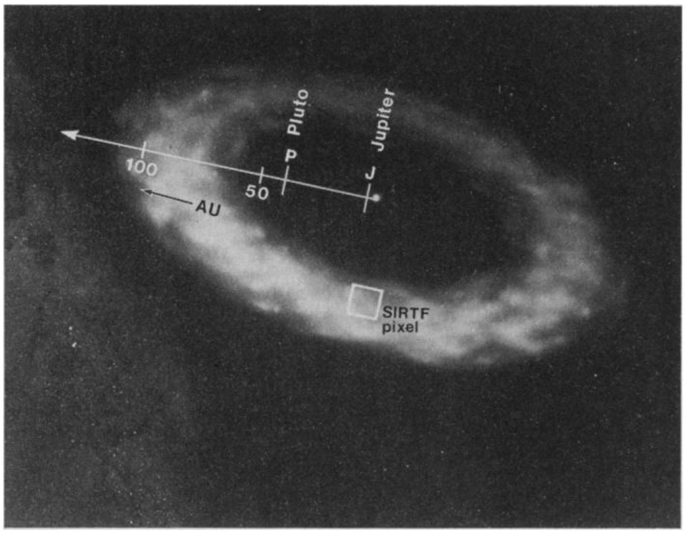


Fig. 1. Artist's concept of the particle cloud around Vega. The dimensions of the cloud have been estimated from the IRAS photometry (*9*); the scale of the solar system is superposed. One astronomical unit (Au) is the distance from Earth to the sun. The pixel size of SIRTF applies to the conventional diffraction limit for both the camera and spectrograph at 5 μm; it shows our ability to make detailed measurements of the structure and other physical properties of this system.

resolution camera covering the 3- to 30-μm region with large arrays of detectors; (ii) an imaging photometer, with small arrays of high-sensitivity detectors covering the wavelength range 3 to 700 μm; and (iii) a spectrograph operating from 2.5 to 200 μm with spectral resolutions of 2 and 0.1 percent. The instruments will be built by teams selected in July 1984; during the SIRTF flight, they would be used by the general scientific community. These instruments closely parallel the capabilities considered fundamental in any modern optical observatory. With them, we would follow up on IRAS much as large optical telescopes have allowed detailed study of the objects discovered in the Palomar Optical Sky Survey.

Formation of Planets

The fossil record of the solar system is found in asteroids, planetary satellites, and comets. These small, cool bodies preserve samples of the material that condensed in the protosolar and protoplanetary nebulae. Ices such as H_2O, CO_2, CH_4, NH_3, and NH_4NS are expected to be common because they are made of abundant elements, and H_2O and CH_4 have already been identified on some of the brighter objects. Water has also been discovered chemically bound in the minerals on some asteroids (*8*). These materials all have very strong bands in the 3- to 4-μm range, where they could be detected and identified by SIRTF in spectra of reflected solar radiation.

Among the most exciting discoveries of IRAS are the clouds of millimeter-sized particles found around Vega, β Pic, and, apparently, dozens of other stars in the neighborhood of our solar system (*9*). For the first time, we can contrast bodies in the solar system with ones that formed and grew around other stars. With SIRTF, it should be possible to study systems such as these using both imaging and spectroscopy (Fig. 1).

The particle clouds around Vega and β Pic are very different from the planets around our sun; they are detectable only because their mass is finely divided and hence has a large surface area to absorb energy from the central star. However, they make it seem plausible that planetary systems are to be found around many stars. Indeed, years of precise measurements of stellar positions show that a few nearby stars wobble tantalizingly, as if massive planets were orbiting them (*10*). Direct detection of these planets, most of which are indicated to be 2 to 50 times as massive as Jupiter, would allow study of their physical properties, a fundamental step if we are to understand planetary systems other than our own.

Theoretical calculations indicate that fusion reactions should occur only in objects at least 8 percent as massive as the sun. Objects less massive do not generate thermonuclear energy to become stars but retain gravitational energy released in their initial collapse and radiate it away slowly at infrared wavelengths (*11*). Jupiter, at 0.1 percent of the solar mass, releases energy at twice the rate at which it absorbs it from the sun. The amounts of trapped energy and its rate of release increase rapidly with mass between 0.1 and 8 percent of the solar mass; the surface temperature of these objects is expected to range from about 100 K to 2000 K, with wavelengths of maximum brightness between 40 and 2 μm. Recently, observations at 2 μm with large ground-based telescopes have yielded the detection of a massive planet near the faint star VB 8 (*12*). Particularly with the application of the superresolution image-processing techniques discussed below, SIRTF could search the regions outside 15 astronomical units (AU) of the 50 nearest stars (Fig. 1). It would detect any planets of three Jupiter masses or greater.

Our galaxy contains hidden mass that is felt gravitationally and is detected through its influence on galactic rotation. This material accounts for at least 75 percent of the mass of the galaxy and for a similar percentage in many others (*13*). The prevalence of the hidden mass is the outstanding question regarding the past and future of the universe; the known mass density is insufficient to bind the universe gravitationally and implies that it is open—that it will expand forever (*14*). However, if sufficient hidden mass also lies outside galaxies, or even extends into the outer reaches of galaxies, the universe may be closed—its expansion will eventually reverse. All efforts to detect directly this dominant constituent of galaxies and possibly of the universe have failed. Perhaps we have seriously underestimated the number of "free flying" planets—frequently called brown dwarfs—circulating among the stars. If so, SIRTF should detect several hundred of these objects in a deep survey of a few square degrees of sky; it may be our only means of detecting this form of cold, dark matter.

Infrared measurements of massive planets and brown dwarfs would probe the behavior of the hydrogen in their cores, at pressures well above those attainable on Earth. They would determine the precise mass required for initiation of nuclear processes in the core of a star, and they should show the effects of hydrogen phase transitions as a function of mass of the object. SIRTF observations of other planetary systems and of primitive matter in our own system should lead to a deeper understanding of how, where, and how frequently planets form. We would attain a much broader perspective of the origin of the solar and other planetary systems, a critical factor influencing the prevalence of life in the universe.

Formation of Stars

Stars form through the condensation of interstellar clouds of gas, but this metamorphosis of gas cloud into young star occurs inside a cocoon of dust that obscures our view at all but infrared and radio wavelengths. The star spends most of its infancy deriving energy from gravitational collapse and is at temperatures as low as 10 to 15 K, so that it radiates only at long infrared wavelengths. Even when the temperature of the forming star rises to thousands of degrees,

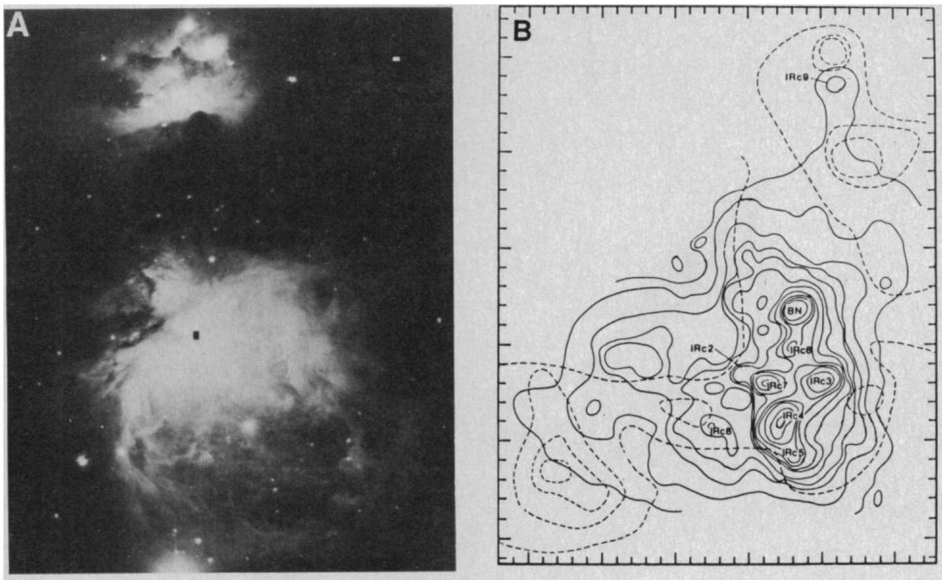


Fig. 2. Studies of nearby star formation. (A) A photograph of the Orion nebula, which consists of glowing gas excited by relatively young stars near its center. The box indicates a region where much younger stars are forming. (B) An infrared map (at 20 μm) (*38*) of the star-forming region within the box in (A). The solid contours show the distribution of infrared flux, and the dotted contours show regions of strong emission by molecular hydrogen. (C) A predicted infrared spectrum of this star-forming region (*39*). The spectrum extends from 1 to 100,000 μm and shows a strong continuum flux, contributed by heated dust, and a wealth of atomic fine structure and molecular emission lines.

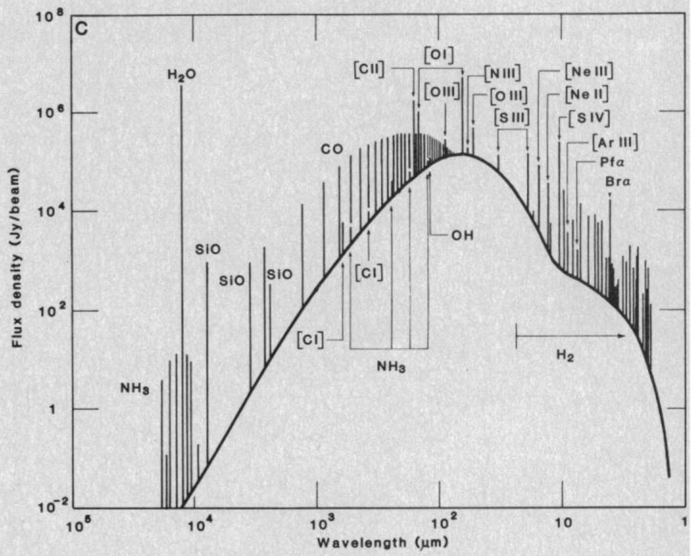
the surrounding dust absorbs virtually all the optical and ultraviolet radiation and reemits it in the infrared (*15*). Consequently, little is known about any stage of this process; the observational uncertainties in the initial densities, temperatures, and dynamical states of regions of star formation are so great that realistic boundary conditions for theoretical studies have not yet been established.

With SIRTF, a first step would be to take pictures of the dense gas clouds near the sun, providing a complete set of snapshots of all the stages of star formation. Individual objects in these snapshots would be scrutinized carefully with the SIRTF spectrograph (Fig. 2). Together, the imaging and spectroscopy could define the evolution from gas cloud to mature star. In addition, the assembled data for a whole cloud would reveal the distribution of fragment size, which depends on the mechanism of fragmentation in the cloud and determines the mass distribution of the forming stellar population.

The only stage in stellar evolution that has never been clearly identified is the first one—the protostar. Presumably, IRAS has now detected many protostars that need to be distinguished from other sources. This goal can be achieved by observing emission lines from the CO and NH_3 molecules that are thought to be excited in protostellar material. These lines are sensitive monitors of the temperature and density of the emitting region. At the low temperature of a quiescent molecular cloud, the excitation produces predominantly radio lines; in hot gas around nearly formed stars, the near infrared CO lines dominate. The far infrared lines observable with SIRTF should be prominent where conditions are appropriate for a protostar.

Various current theories predict distinct forms for the large-scale patterns of star formation over a galaxy and have profoundly different consequences for galaxy formation and evolution (*16*). These patterns of star formation are best viewed in external galaxies; from our vantage point within the Milky Way, it has always been hard to distinguish the overall design. SIRTF's imagers would map the structure and pattern of star formation on a galactic scale for the first time. Figure 3 compares the IRAS image of the nearest large spiral galaxy, M31, with the expected capabilities of an SIRTF camera.

Such images can also test how star formation is influenced by environment. For example, star formation may proceed differently in the Large Magellanic Cloud (LMC)—the nearest external galaxy—than near the sun (*17*). SIRTF could test this possibility, since

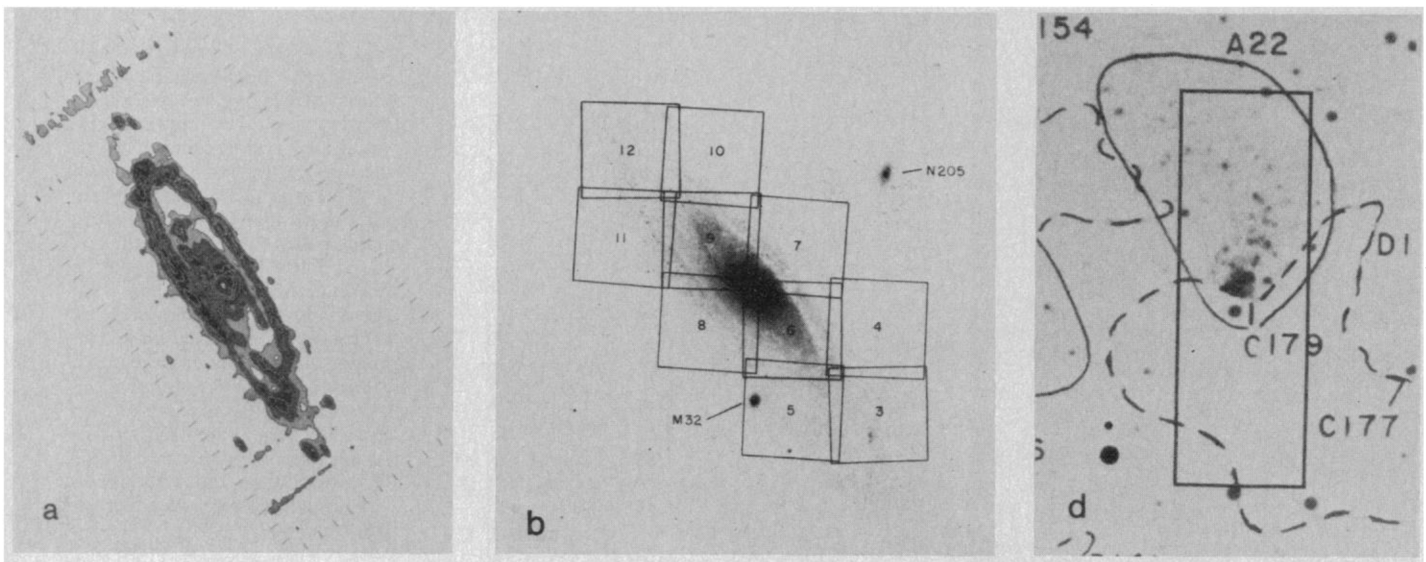


it could detect any protostars of solar mass or greater in the LMC. In fact, SIRTF could study star formation in the LMC with as much detail as is now achieved in most of the Milky Way.

Before IRAS, galaxies had been found that release 80 to 90 percent of their energy in the far infrared. Frequently, intense ongoing star formation accounts for this energy, which is absorbed by the interstellar dust and is reemitted in the infrared. Because of the obscuring dust, the extent of star formation had been overlooked in optical studies. IRAS has discovered galaxies in which 99 percent or more of the total energy is emitted in this fashion; in extreme cases, the young stars emit the energy of a trillion suns, which is 100 times the entire output of our galaxy and comparable in power with quasars (*18*). Deep imaging with SIRTF could locate infrared galaxies far back in time; spectroscopy could probe conditions within them.

Formation of Galaxies

Galaxy evolution derives from the life histories of stars. By the time forming stars emerge from interstellar clouds, they have reached high temperatures (3,000 to 60,000 K) and emit energy



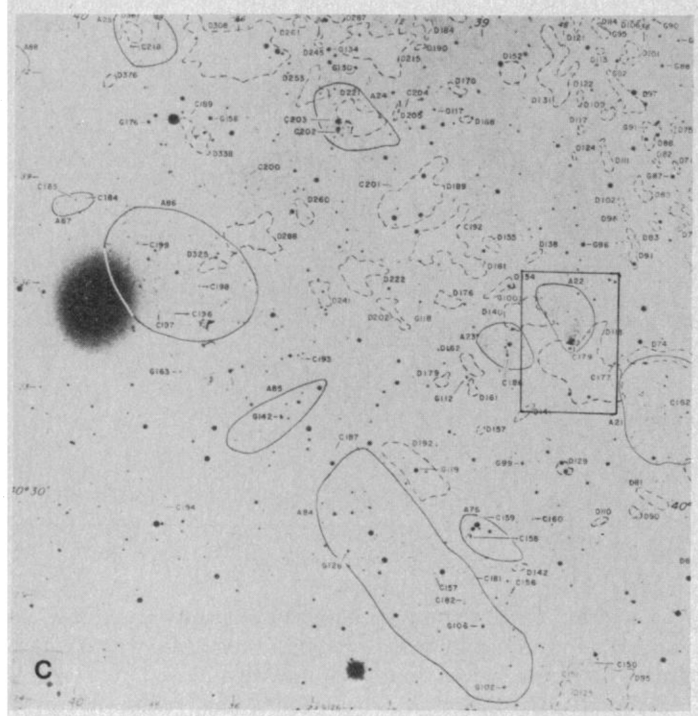


Fig. 3. Star formation in other galaxies. (a) The IRAS map of the Andromeda Nebula (M31) at 60 μm (*40*). (b) An optical photograph of M31 to the same scale, divided into regions for more detailed studies of star formation (*41*). (c) The region indicated by box 5 in (b). (d) The same region of star formation indicated by the box in (c), with the superposed IRAS beam; within the beam can be seen a young stellar association partially obscured by a dark interstellar cloud. The two dots in the lower left corner indicate the resolution attainable by SIRTF at 60 μm before and after the application of superresolution.

primarily in the visible and ultraviolet. Decades of study at these wavelengths have traced their subsequent evolution and shown it to be consistent with the Russell Vogt theorem: the fate of a star is determined by its mass and composition at formation.

The development of a galaxy is studied by taking an accurate census of its vast population of stars and comparing it with a computer model of stellar evolution. Since neither the population nor the evolution is known perfectly, a variety of hypothetical models must be produced and checked against new observations. Current models suggest that galaxy formation is marked by an episode of very rapid star formation, including creation of large numbers of massive, high-luminosity stars. During this stage, the luminosity of the protogalaxy should be very high; all ordinary galaxies like our own will have outputs about 100 times what they are today (*19*) and may resemble in many respects the most extreme nearby galaxies discovered by IRAS.

Although these predictions are reasonably specific, extensive optical searches for protogalaxies have been unsuccessful, possibly because of the cosmic redshift. The peak of the spectrum of even nearby galaxies lies in the near infrared; this peak appears within a few tens of millions of years after the initiation of star formation and is a persistent feature of the galaxy's energy distribution from that time on. If we look back in time to when the universe was only 10 percent as old as it is now (*20*), this peak will be redshifted to a wavelength of about 15 μm, and only a tiny fraction of the emission of the galaxy will appear in the optical.

The SIRTF cameras will observe the progenitors of galaxies like our own as early as 4 percent of the current age of the universe, and the more luminous progenitors of giant elliptical galaxies should already be seen at 1 percent of this time. Preliminary identifications and redshifts and ages will be estimated from the shapes of the spectra and location of the spectral peaks. The density of protogalaxies on the sky is strongly dependent on models of the early universe, but in any case we expect to find more than one per square arc minute. With a candidate list of protogalaxies selected by these criteria, the spectrograph on SIRTF should be able to confirm their identification by detecting spectral features, such as hydrogen recombination lines excited by young, hot stars, or the absorption features due to the CO molecule in the atmospheres of cool stars.

Modern theories of the earliest stages of the universe are primarily concerned with the formation of density fluctuations and their growth into galaxy clusters, galaxies, and stars. A deep SIRTF survey would contribute immensely to these theories.

Cosmic Energy Sources

A new era in astronomy began 25 years ago when the discovery of quasars shattered astronomers' theories of a placid universe dominated by stellar processes. Quasars are now known that release

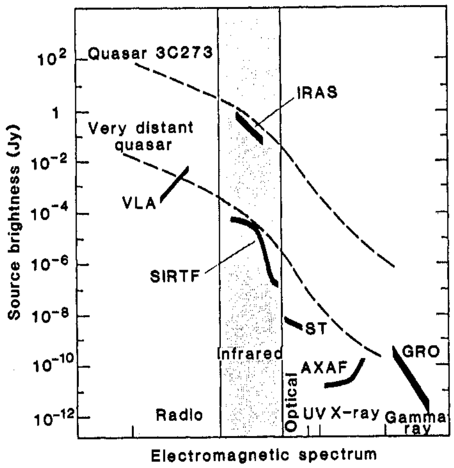


Fig. 4. Studies of quasars. The observed spectrum of the brightest quasar, 3C273, has been scaled down to show how the spectrum of a very distant quasar should behave. The sensitivity of a number of existing or planned facilities is compared with this spectrum—the Very Large Array (VLA) in the radio, the Infrared Astronomy Satellite (IRAS) and Space Infrared Telescope Facility (SIRTF) in the infrared, the Hubble Space Telescope (ST) in the optical and ultraviolet, the Advanced X-Ray Astrophysics Facility (AXAF) in the x-ray, and the Gamma Ray Observatory (GRO) in the gamma-ray. The performance of IRAS is at least as good as that of any other existing infrared telescope except near 10 μm, where in long integrations ground-based telescopes can detect sources about ten times fainter.

energy at the rate of 1000 Milky Way galaxies from a volume barely larger than the solar system. At one time, astronomers tried to avoid the implications of these extreme conditions by placing quasars nearby, perhaps within or ejected from the Milky Way. Quasars have now been detected at the nuclei of a number of galaxies, eliminating this possibility (*21*). Neither the source of quasar energy nor how it is converted into radio, infrared, optical, and x-ray photons is understood. The most popular theory invokes a massive black hole, which releases energy by assimilating the interstellar clouds of the host galaxy.

Although quasars were discovered because of their radio emission, it is now known that typical ones emit hardly at all in the radio, faintly in the x-ray, and predominantly in 12 octaves of the spectrum spanning the ultraviolet, optical, and infrared (Fig. 4). Measurements over most of this spectral region are currently possible for only a few dozen of the brightest quasars; the other quasars can only be measured over five octaves, and the underlying spectrum over much of these five octaves is heavily confused by superposed emission of excited gas. Measurements throughout the infrared are needed to find distinct spectral components associated with different parts of the source, to determine the time scales of their flux-level variations, and to examine how the components interact during variations. These observations require SIRTF.

Because of their extreme energy outputs, quasars are the most distant objects known and a probe of conditions in the early universe. We find that their number rose rapidly from the earliest visible stages to a maximum at about 15 percent of the age of the universe. As the universe continued to evolve, the number fell rapidly, presumably as their energy sources were consumed (*22*). When we compare the maximum density of quasars with the density of nearby galaxies, we conclude that a few percent of the galaxies must harbor burned-out quasars in their nuclei. A similar percentage of galaxies is observed to have nuclei with compact active sources unexplained by any stellar processes, and a controversy is currently raging over the possibility that our galaxy is among them (*23*). Are these galaxies the dying quasars? Can we learn about quasars by studying nearby active galaxies? A deep SIRTF survey with subsequent spectroscopic measurements across the ultraviolet, optical, and infrared could determine the cosmic evolution of active galaxies and answer these questions.

Attempts a century ago to understand the source of the sun's energy present a humbling analogy to our current difficulties with the energy sources in quasars; it is not at all clear that current physics is adequate for the task. This possibility is more exciting than frustrating, however, because further progress may teach us new physics. Information about quasar evolution and source components and their variations and interactions is essential to this progress.

Unexpected Discoveries

In astronomy, virtually every substantial advance in wavelength coverage, time resolution, or sensitivity has dramatically altered our view of the universe (*24*). Optical telescopes began by providing the final proof of the Copernican view of the solar system and eventually revealed our sun as an insignificant star in an insignificant galaxy. Radio astronomy has shown us quasars, pulsars, apparent faster-than-light motions, and narrow, collimated jets longer than whole galaxies. X-ray astronomers have found neutron stars, bursters, and possibly black holes. In the infrared, we have discovered primitive planetary systems and powerful galaxies completely hidden in dust shells. In fact, the greatest discovery of all has been that the universe is so incredibly complex and interesting that it continually outstrips our imagination.

Many of the most important discoveries of IRAS will remain unappreciated without SIRTF, just as we would know far less about quasars if radio astronomy had stopped with its first all-sky catalog. In addition, the sensitivity of SIRTF would allow us to explore a new range of potential discoveries. SIRTF would see so much farther into space it could make a very deep, small area survey to complement the all-sky survey already completed by IRAS. For example, in 5 minutes of integration at 10 μm, SIRTF could detect objects 5000 times fainter than the limit of the IRAS catalog. At this level of sensitivity, each square degree surveyed is equivalent to ten times the volume of space covered in the entire IRAS survey.

In addition to probing a very large volume of space, these surveys would cross critical sensitivity thresholds for discoveries beyond the grasp of IRAS or any other instrument. Examples include finding brown dwarfs and protogalaxies, tracing star formation over the lifetimes of galaxies, and sampling the cosmic evolution of active galaxies. Fundamental as these examples seem, they may be overshadowed by discoveries we cannot currently imagine.

Infrared Astronomy Today

Existing ground-based and airborne telescopes are being used for the first studies of IRAS sources and to achieve the goals set by the Field Report. Earth's atmosphere has a number of spectral "windows" that are transparent in the infrared. Water vapor is the primary atmospheric absorber infringing on these windows. Hence, large telescopes have been optimized for infrared performance and placed on mountains above most of the atmospheric water vapor. Even so, there are wavelengths where the atmosphere is opaque from the ground (including the entire region from 40 to 300 μm), so that observations are made with smaller telescopes carried by airplanes and balloons (*25*).

The power of these instruments will be expanded with advanced detector systems and eventually with a next generation of larger telescopes, such as the 10-m Keck Telescope and the 15-m National New Technology Telescope (NNTT) on the ground (*26*) and a 3-m balloon or airborne telescope. The large apertures of these instruments make possible excellent sensitivity in the near infrared and provide for high spectral and angular resolution at longer wavelengths.

Despite the usefulness of these telescopes, Earth's surface and lower atmosphere are exceedingly hostile environments for infrared astronomy. An infrared detector on an ambient temperature telescope receives a strong background flux of thermal emission from the telescope and the atmosphere (Fig. 5). This background is typically many orders of magnitude stronger than the flux from the astronomical source under study. The background could be removed by cooling the telescope. However, to avoid condensation on its optics, the telescope cannot be cooled below the dew point, which is usually not far below the ambient temperature.

Even under the most favorable conditions, infrared observations in the presence of this bright background are as difficult and inefficient as optical observations of faint stars in broad daylight. Observing techniques have become so sophisticated that it is routine to measure sources contributing less than 10^{-6} the total flux falling on the detector (*27*). Nevertheless, statistical noise due to the background photons is an unavoidable performance limitation on an ambient-temperature infrared telescope, a limit that has now been reached across the entire infrared band.

The impact of thermal background can be appreciated from the performance of IRAS, the first cooled telescope for space infrared astronomy. The absence of background emission from the telescope and from Earth's atmosphere allowed IRAS to complete its survey in 10 months; an equivalent survey with a 5-m aperture ground-based telescope in the two accessible IRAS bands would have required 100,000 years (assuming perfect weather and 24-hour-per-day operation). The euphoria over the success of IRAS is tempered by the realization that, when the satellite's coolant was exhausted on 22 November 1983, we lost the ability to detect again many of the sources it had discovered.

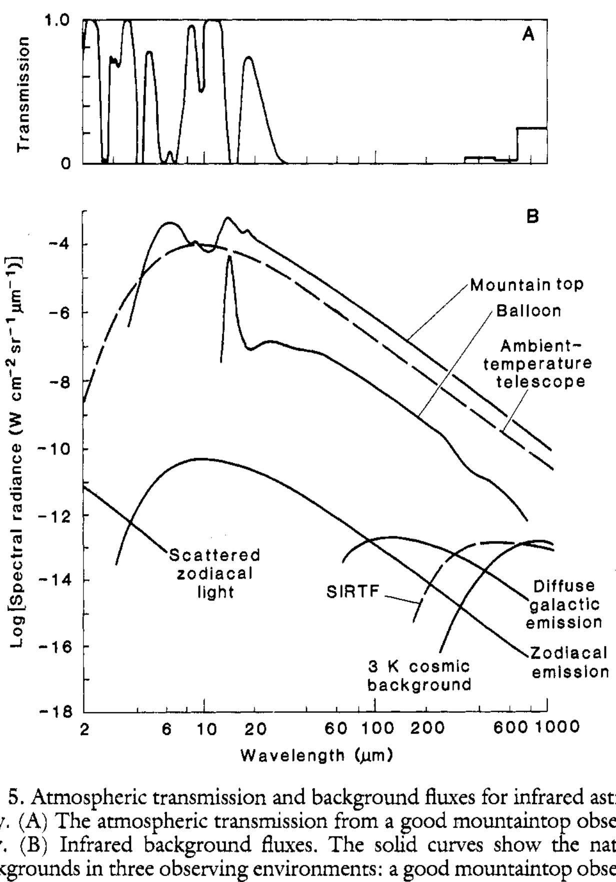


Fig. 5. Atmospheric transmission and background fluxes for infrared astronomy. (A) The atmospheric transmission from a good mountaintop observatory. (B) Infrared background fluxes. The solid curves show the natural backgrounds in three observing environments: a good mountaintop observatory, high balloon altitudes, and space, where it is the sum of scattering and emission by zodiacal dust grains, emission by diffuse galactic dust, and the 3 K universal background. The atmospheric background from airplane altitudes is intermediate between the curves for the mountain observatory and space. The dashed curves show the background contributions from optimized infrared telescopes: an ambient-temperature instrument (such as would be used from the ground, airplanes, or balloons) and SIRTF. The total background at the infrared detector is the sum of the natural and telescopic contributions.

The Future of Infrared Astronomy in Space

IRAS was optimized as a survey mission: it could not point and integrate efficiently; it provided modest spectral and angular resolution; and its detector sensitivities were limited by requirements for fast response. A cooled telescope adequate for a thorough follow-up of IRAS need not be substantially larger than IRAS itself, so long as it provides good images and accurate pointing and uses the best available detector arrays. Such a facility could detect individual compact sources 1,000 to 10,000 times fainter than the survey limit. It would have ample sensitivity for spectroscopy and imaging of any IRAS source. Among all proposed new astronomical facilities for any wavelength region, the largest gain in sensitivity by far would come from a cooled infrared observatory in space.

A cooled infrared telescope of 0.9-m aperture operating from a satellite was recommended to NASA more than 15 years ago by the Astronomy Missions Board (*28*). In 1973, the Space Science Board of NAS identified such a telescope as a possible Space Shuttle facility (*29*). The following year, the Space Science Board endorsed a two-step approach to infrared astronomy in space, consisting of a survey satellite and a 1-m cooled telescope to "be flown soon after the results of the Infrared Survey Satellite are digested" (*30*). SIRTF is the embodiment of these recommendations and was assumed by the Field Report (*7*) to be a precursor of its recommended new missions.

SIRTF (Fig. 6) would have a 0.85-m aperture, with optics and detectors cooled to less than 7 K with superfluid liquid helium (*31*). Although it would be carried into low orbit by the Space Shuttle, an additional propulsion system would boost it to an orbital altitude of 700 to 900 km. IRAS showed that the environment at this altitude is benign for a cooled telescope; therefore, SIRTF's performance will not be degraded by thermal radiation from Earth or the sun, by cosmic rays or trapped energetic charged particles, or by contamination from the residual atmosphere. The SIRTF telescope is compatible either with a free-flying spacecraft or with operation from a standardized platform that might be part of the Space Station program. In either case, SIRTF would be a long-duration facility; on-orbit servicing and coolant replenishment would be provided by the Space Shuttle or at the manned Space Station.

Three other space missions can extend certain aspects of the results from IRAS. The Spacelab 2 Infrared Telescope, launched in July 1985, mapped the sky for very extended sources and tested the suitability of the Space Shuttle for other infrared packages. The Cosmic Background Explorer, due for launch in 1988, will provide a more sensitive and complete look at the large-scale cosmic background and will provide measurements at the longest infrared wavelengths (*32*). The European Space Agency is planning the Infrared Space Observatory, a relatively modest cooled infrared observatory (*33*). However, only SIRTF will combine a very broad range of capabilities, an optimized orbit, and a long lifetime with coolant replenishment.

SIRTF would also take full advantage of recent advances in infrared detectors. Arrays are now available containing thousands of elements, each sensitive enough to reach the background noise limit in space (*34*). Below 30 μm, these arrays use high-purity silicon

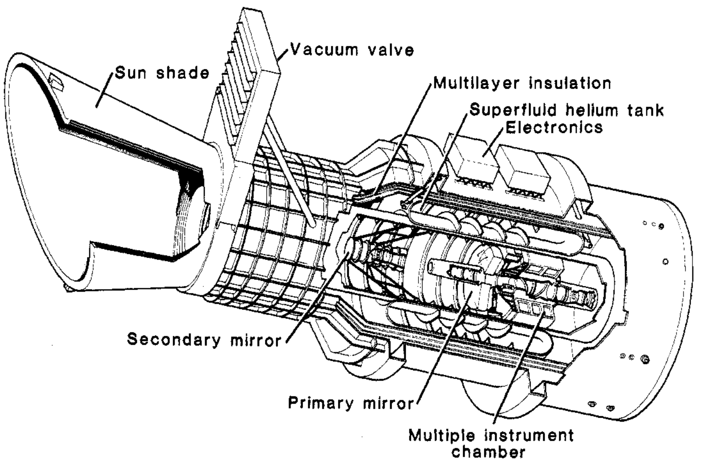


Fig. 6. Cutaway drawing of the SIRTF telescope, showing a number of major subsystems.

detectors, doped (*35*) to give photoconductive response in the infrared. Between 1 and 5 μm, arrays of indium antimonide detectors are an alternative; between 30 and 200 μm, doped germanium photoconductors can be used (*36*). In all cases, the electrical current in each detector is regulated by the rate at which the detector absorbs photons. The charge from this current is accumulated by one member of an array of field-effect transistors, which can be read out and reset after some seconds of integration. These detector-transistor arrays will greatly accelerate spectroscopy by providing a detector for each spectral element. They will also allow us to form true infrared images for the first time.

With these detectors, SIRTF's performance would be limited at most wavelengths only by thermal emission from zodiacal dust grains around the sun, which constitutes the basic limit to infrared astronomy from the vicinity of Earth (Fig. 5). Over the entire 3- to 150-μm spectral range, this background is up to 10^7 times fainter than that experienced by ground-based and airborne infrared instruments. The huge reduction in background flux allows SIRTF its sensitivity gain of 1000 or more over these five octaves of the spectrum.

Besides improved sensitivity, there is an additional advantage to imaging in a space environment. Because of the high signal-to-noise ratio, stable pointing, and lack of a variable atmospheric blur, image processing can provide significantly better angular resolution than the "theoretical limit" set by the conventional Rayleigh criterion (*37*). This capability is particularly important near 100 μm, where existing telescopes have not achieved resolution better than 30 arc seconds. Application of "superresolution" techniques in this region should permit imagery several times sharper with SIRTF (Fig. 3), allowing accurate comparisons to be made with imaging obtained with modern radio, near infrared, optical, and x-ray facilities.

Conclusions

SIRTF is an integral part of the group of great space observatories, which also includes the Hubble Space Telescope, the Gamma Ray Observatory, and the Advanced X-Ray Astrophysics Facility. Combined with modern ground-based radio telescopes, these instruments will for the first time give us a unified view of celestial objects from the radio to the gamma ray regions of the spectrum, limited only by the unavoidable cosmic background noise in the general vicinity of Earth. Within this range, the infrared region provides a number of unique perspectives particularly regarding cosmic birth—of planets, stars, galaxies, active galactic nuclei, and quasars. IRAS has begun to paint a broad view of the infrared universe; SIRTF will expand this picture with the largest advance in capability offered by any proposed astronomical facility.

REFERENCES AND NOTES

1. J. A. Eddy, *J. Hist. Astron.* **3**, 165 (1972).
2. Sir William Herschel was trained as a musician, but with his sister, Caroline, he dedicated his life to astronomy. His discovery of Uranus in 1781 led George III to make him the first Astronomer Royal.
3. The third Earl of Rosse advanced the methods for casting speculum metal telescope mirrors; in 1845 he built a telescope with a 72-inch aperture. This instrument remained the largest ever built for 70 years.
4. G. Neugebauer *et al.*, *Science* **224**, 14 (1984); H. J. Habing and G. Neugebauer, *Sci. Am.* **251**, 49 (November 1984).
5. Temperatures in the following are expressed in degrees Kelvin, or K. The Kelvin scale places 0 K at absolute zero and the freezing point of water at 273 K.
6. Wavelengths in this article will be expressed in micrometers, one-millionth of a meter. The wavelength of visible light is about 0.5 μm.
7. G. B. Field *et al.*, *Astronomy and Astrophysics for the 1980's* (National Academy Press, Washington, DC, 1982), vol. 1.
8. H. P. Larson, *Annu. Rev. Astron. Astrophys.* **18**, 43 (1980).
9. H. H. Aumann *et al.*, *Astrophys. J.* **278**, L23 (1984).
10. H. Abt, *Sci. Am.* **236**, 96 (April 1977); D. C. Black, *Space Sci. Rev.* **25**, 35 (1980).
11. D. J. Stevenson, *Proc. Astron. Soc. Australia* **3**, 227 (1978).
12. D. W. McCarthy, R. G. Probst, F. J. Low, *Astrophys. J.*, in press.
13. V. C. Rubin, *Sci. Am.* **248**, 96 (June 1983); J. N. Bahcall, *Astrophys. J.* **276**, 169 (1984).
14. D. A. Dicus, J. R. Letaw, D. C. Teplitz, V. L. Teplita, *Sci. Am.* **248**, 90 (March 1983).
15. A. P. Boss, *ibid.* **252**, 40 (January 1985); C. G. Wynn-Williams, *Annu. Rev. Astron. Astrophys.* **20**, 587 (1982); R. D. Gehrz, D. C. Black, P. M. Solomon, *Science* **224**, 823 (1984).
16. N. Scoville and J. S. Young, *Sci. Am.* **250**, 42 (April 1984); D. M. Elmegreen and B. G. Elmegreen, *Astrophys. J. Suppl.* **54**, 127 (1984).
17. T. J. Jones, A. Hyland, P. M. Harvey, B. Wilking, M. Joy, J. A. Thomas, in *Airborne Astronomy Symposium*, H. A. Thronson and E. F. Erickson, Eds. (NASA Conference Publ. 2353, Government Printing Office, Washington, DC, 1984), p. 272.
18. R. E. Schild, *Sky and Telescope* **69**, 24 (1985); B. T. Soifer *et al.*, *Astrophys. J.* **283**, L1 (1984); G. H. Rieke *et al.*, *ibid.* **290**, 116 (1985).
19. D. L. Meier and R. A. Sunyaev, *Sci. Am.* **241**, 130 (March 1979); R. A. Sunyaev, B. M. Tinsley, D. L. Meier, *Comments Astrophys. Space Phys.* **7**, 183 (1978).
20. The universe is thought to have begun with the Big Bang about 15×10^9 years ago and to have expanded since then to its current state. Given a model of the rate of universal expansion, the age of any astronomical object as a percentage of the age of the universe can be derived precisely from the extent of its cosmic redshift.
21. J. B. Hutchings, *Publ. Astron. Soc. Pac.* **95**, 799 (1983).
22. P. S. Osmer, *Sci. Am.* **246**, 126 (February 1982); M. Schmidt and R. F. Green, *Astrophys. J.* **269**, 352 (1983).
23. D. A. Allen and R. H. Sanders, *Nature (London)*, in press.
24. M. Harwit, *Cosmic Discovery* (Basic Books, New York, 1981).
25. Major ground-based infrared telescopes include the NASA Infrared Telescope Facility (3-m aperture) on Mauna Kea, the Multiple Mirror Telescope (4.5-m aperture) on Mt. Hopkins in Arizona, and the Wyoming Infrared Observatory (2.3-m aperture) on Mt. Jelm. The United Kingdom has also built a 3.8-m infrared telescope on Mauna Kea. A 0.9-m telescope is carried aloft in a C-141 transport airplane in the Kuiper Airborne Observatory, and a number of telescopes of similar aperture are carried by balloons.
26. Plans for the next generation of large telescopes are discussed by E. J. Wampler [*Phys. Today* **35**, 44 (1982)]; and in *Very Large Telescopes, Their Instrumentation and Programs*, M.-H. Ulrich and K. Kjar, Eds. (IAU Colloquium 79, European Southern Observatory, Garching bei München, Federal Republic of Germany, 1984)].
27. Techniques used with ambient temperature telescopes are reviewed by B. T. Soifer and J. L. Pipher [*Annu. Rev. Astron. Astrophys.* **16**, 335 (1978)] and by F. J. Low and G. H. Rieke [in *Methods of Experimental Physics* (Academic Press, New York, 1974), vol. 12, part A, pp. 415–462].
28. Astronomy Missions Board, *A Long-Range Program in Space Astronomy* (NASA SP-213, Government Printing Office, Washington, DC, 1969), pp. 88–89.
29. Space Science Board, *Scientific Uses of the Space Shuttle* (National Academy Press, Washington, DC, 1974).
30. ——, *Opportunities and Choices in Space Science, 1974* (National Academy Press, Washington, DC, 1975).
31. *SIRTF, Free Flyer Phase A System Concept Description* (NASA Document PD-1006, Ames Research Center, Moffett Field, CA, 1984).
32. The Spacelab 2 Infrared Telescope, the Cosmic Background Explorer, and other NASA programs in the space infrared astronomy are reviewed by M. G. Hauser [*Proc. Soc. Photo-Opt. Instrum. Eng.* **280**, 2 (1981)].
33. R. Emery, in *Second ESO Infrared Workshop*, A. F. Moorwood and K. Kjar, Eds. (European Southern Observatory, Garching bei München, Federal Republic of Germany, 1982), p. 425.
34. C. R. McCreight, Ed., *Infrared Detector Technology Workshop*, Ames Research Center, Moffett Field, 11 and 12 July 1983 (Government Printing Office, Washington, DC, 1983); C. R. McCreight, J. H. Goebbel, M. E. McKelvey, P. S. Stafford, J. H. Lee, *Soc. Photo-Opt. Instrum. Eng. Int. Tech. Symp.* **28**, 501 (1984).
35. Doping refers to the addition of carefully regulated amounts of impurities to semiconductor materials such as silicon and germanium. This process can produce

modes of electrical conductivity that are excited by the small amounts of energy released when an infrared photon is absorbed.
36. For wavelengths no longer than 200 μm, the detectors will work on a different principle. With proper doping, silicon and germanium can be made to have electrical resistance strongly dependent on temperature (not photon absorption rate). This material can be used to make detectors sensitive to any wavelength of light that they can absorb. To provide adequate sensitivity for SIRTF, such detectors will have to be cooled with an auxiliary refrigerator to 0.1 to 0.3 K.
37. The Rayleigh criterion states that point sources of equal brightness can only be distinguished if they are separated by an angle (in radians) of at least 1.2 λ/D, where λ is the wavelength of observation and D is the diameter of the telescope. Means to improve on this criterion are discussed, for example, by B. R. Frieden and J. J. Burke [*J. Opt. Soc. Am.* **62**, 1202 (1972)].
38. D. Downes, R. Genzel, E. E. Becklin, C. G. Wynn-Williams, *Astrophys. J.* **244**, 869 (1981).
39. D. M. Watson, in *Galactic and Extragalactic Infrared Spectroscopy*, M. F. Kessler and J. P. Phillips, Eds. (Reidel, Dordrecht, 1984), p. 195.
40. H. J. Habing *et al.*, *Astrophys. J.* **278**, L59 (1984).
41. P. W. Hodge, *Atlas of the Andromeda Galaxy* (Univ. of Washington Press, Seattle, 1981).
42. We thank K. Taylor, L. Yule, and a number of Riekes (particularly F. Rieke) for assistance in preparing this article.

Dynamics of Fractal Networks

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Random structures often exhibit fractal geometry, defined in terms of the mass scaling exponent, D, the fractal dimension. The vibrational dynamics of fractal networks are expressed in terms of the exponent $\bar{\bar{d}}$, the fracton dimensionality. The eigenstates on a fractal network are spatially localized for $\bar{\bar{d}}$ less than or equal to 2. The implications of fractal geometry are discussed for thermal transport on fractal networks. The electron-fracton interaction is developed, with a brief outline given for the time dependence of the electronic relaxation on fractal networks. It is suggested that amorphous or glassy materials may exhibit fractal properties at short length scales or, equivalently, at high energies. The calculations of physical properties can be used to test the fractal character of the vibrational excitations in these materials.

The concept of fractal structure, developed by Benoit Mandelbrot (*1*), has potential utility because it is possible that structures that appear purely random can be described within a geometric mathematical framework. Fractal concepts may describe not only the static geometrical properties of such structures but also their dynamical properties and interactions with external measurement probes. The purpose of this article is to introduce the basic concepts behind the use of fractal geometry in performing these operations.

The fractal description of nature has developed so rapidly and so broadly in recent years, and fractal geometry has become such a powerful tool, that it would be impossible to attempt complete coverage of this subject. Therefore, only the more universal aspects of the structural properties of fractal networks will be analyzed in this article; more specific applications have been described (*2*).

The class of fractal structures treated in this article is limited to those that exhibit "self-similar" geometry. This means that the structure's geometrical properties are indistinguishable as a function of length scale (or resolution). Examining the fractal with ever more finely divided "rulers" would not result in any discernable difference in geometry. Conversely, the length scale of measurement could not be determined solely from observation of the fractal structure. This behavior usually breaks down at very short length scales, appropriate to the atomic or "building block" regime. In many physical systems (such as the percolating network, described later), the structure also ceases to be fractal at very long length scales, where it appears homogeneous or continuous. Mandelbrot (*1*) was the first to determine that many structures in nature exhibit self-similar geometry.

The most easily understood fractal concept is that of density. For fractal structures, this means that there is no constant relation between mass and volume as the length scale is changed. The amount of mass inside a sphere of radius r for a homogeneous (or Euclidean) structure scales as $M(r) = Ar^d$, where A is a numerical constant and d is the spatial or Euclidean dimension (d is 3 in our usual world). Analogously, the amount of mass inside a sphere of radius r for a fractal structure with self-similar geometry scales as $M(r) = Br^D$, where B varies according to the "lacunarity" (*1*) and D is the fractal dimension. In general, D is less than or equal to d because of the "open" character of fractal structures. That is, they tend to exhibit inhomogeneous arrangements of particles, with large amounts of open spaces (voids) and irregular atomic arrangements.

We are now in a position to calculate the density (ρ) of particles inside a sphere of radius r (that is, of volume $V(r) = Cr^d$, where C is a constant) for a fractal structure:

$$\rho(r) = M(r)/V(r) = Br^D/Cr^d \propto r^{D-d} \tag{1}$$

For self-similar structures, the fractal dimension D does not depend on r. This is an extraordinary result, for it implies an order in structures that to a casual observer appear to be completely disordered. It is even more remarkable because densities in seemingly unrelated phenomena in nature appear to behave in such a manner (*1*).

Because D is less than or equal to d, the density falls off with increasing length scale, implying that fractal objects of large size would be extraordinarily light. This must be tempered with the

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