Early Results from the Infrared Astronomical Satellite

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Every time astronomers have surveyed a large fraction of the sky in a new region of the electromagnetic spectrum, they have found different and unexpected phenomena. The Infrared Astronomical Satellite (IRAS), which examined nearly 98 percent of the entire sky at wavelengths in the last significant unexplored portion of the spectrum, is no exception to this rule.

Summary. For 10 months the Infrared Astronomical Satellite (IRAS) provided astronomers with what might be termed their first view of the infrared sky on a clear, dark night. Without IRAS, atmospheric absorption and the thermal emission from both the atmosphere and Earthbound telescopes make the task of the infrared astronomer comparable to what an optical astronomer would face if required to work only on cloudy afternoons. IRAS observations are serving astronomers in the same manner as the photographic plates of the Palomar Observatory Sky Survey; just as the optical survey has been used by all astronomers for over three decades, as a source of quantitative information about the sky and as a "roadmap" for future observations, the results of IRAS will be studied for years to come. IRAS has demonstrated the power of infrared astronomy from space. Already, from a brief look at a miniscule fraction of the data available, we have learned much about the solar system, about nearby stars, about the Galaxy as a whole and about distant extragalactic systems. Comets are much dustier than previously thought. Solid particles, presumably the remnants of the star-formation process, orbit around Vega and other stars and may provide the raw material for planetary systems. Emission from cool interstellar material has been traced throughout the Galaxy all the way to the galactic poles. Both the clumpiness and breadth of the distribution of this material were previously unsuspected. The far-infrared sky away from the galactic plane has been found to be dominated by spiral galaxies, some of which emit more than 50 percent and as much as 98 percent of their energy in the infrared—an exciting and surprising revelation. The IRAS mission is clearly the pathfinder for future missions that, to a large extent, will be devoted to the discoveries revealed by IRAS.

During the last two decades infrared observations have proved to be sensitive indicators of cold solid material in the universe, both in regions of star formation (*1*) and in many galaxies (*2*). Infrared astronomy has been hampered, however, by the lack of a sensitive unbiased survey of the sky; IRAS was designed to fill that need. Early scientific results of that mission are published in the *Astrophysical Journal Letters* in March 1984. In this article, we review the contents of some of these letters.

The IRAS Mission and Spacecraft

The mission of IRAS was to make a complete, sensitive, and unbiased survey of the entire sky at wavelengths of 12, 25, 60, and 100 μm and to make pointed observations of preselected objects with a sensitivity at least five times better than achievable in the survey proper. The satellite was launched into orbit in January 1983 and worked almost perfectly until its liquid helium coolant was depleted in November 1983.

In order to achieve the desired sensitivity, it was necessary to place an instrument above the absorption and thermal emission of the earth's atmosphere and to use a telescope and detectors cooled by liquid helium. Sixty-two solid-state detectors were used to cover the four broadbands centered at the wavelengths mentioned above. The resultant system was approximately 100 times more sensitive than previous infrared astronomical instruments and was able to survey nearly the whole sky several times over.

The satellite was launched into a nearly polar orbit at an altitude of 900 km over the earth's day-night terminator. The orbit was tipped slightly from a polar orbit to cause it to precess 1° per day to keep the orbital plane nearly perpendicular to the earth-sun line. The motion of the satellite in its orbit plus the ability to scan up to 30° from the local vertical enabled IRAS to view the entire sky in just under 7 months. The spacecraft and its mission are described in (*3*) and (*4*).

An elaborate scheme of confirmation was built into the design of the flight hardware and data reduction software to identify astronomical sources and to reject the signals from cosmic-ray events in the detectors and from orbiting space debris. For a source to be accepted as an inertially fixed, celestial object it had to be sighted on time scales of seconds, hours, and weeks. Each source was measured by two or more detectors in one scan over its position (seconds-confirmation) and again in another seconds-confirmed scan occurring a few hours later (hours-confirmation). Another hours-confirmed observation, again consisting of two seconds-confirmed sightings, was obtained a week or two later (weeks-confirmation). Moving objects, such as asteroids and comets, are identified at the times of hours- and weeks-confirmation.

The Survey

The survey of 95 percent of the sky at the weeks-confirmed level constituted the first IRAS sky survey. Approximately 75 percent of the sky was scanned with a third hours-confirmed survey beginning 7 months after launch. Before the main all-sky survey was started, an area of ~ 300 square degrees (< 1 percent of the sky) was scanned to the level of three of four hours-confirmations. This extra coverage, called the minisur-

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vey (5), enabled us to estimate that statistically fewer than 0.2 percent of the sources in the catalog of point sources with angular sizes < 1′ are spurious—that is, would not be found by another infrared telescope aimed at the quoted position—and that more than 97 percent of the infrared objects in the region surveyed brighter than the quoted survey limit are to be found in the catalog. These high standards of completeness and reliability apply outside the galactic plane and other confused regions (6). The approximately quarter-million point sources that were twice or more hours-confirmed in the first IRAS survey are plotted in Fig. 1. For comparison, fewer than 500,000 astronomical sources have previously been cataloged; thus IRAS has increased the number of cataloged astronomical sources by 50 percent.

Many different types of celestial objects can be found in the IRAS catalog. Each IRAS wavelength preferentially "sees" different source types. Relatively common red giant stars with surface temperatures < 3000 K and nearby hot stars are seen primarily at 12 μm. Also bright at 12 μm are recently formed stars, regions of ionized gas (H II regions), and hot dust surrounding massive, hot young stars.

Some stars and a substantial population of previously unknown asteroids and comets are found at 25 μm. A prominent class of stars observed at 25 μm are very old giant stars that are enshrouded in dust as they eject a large fraction of their mass back into the interstellar medium (7). Many of these stars are also known as OH/IR stars because of their radio emission in spectral lines of the OH molecule.

As discussed below, galaxies are a third major category of object observed in large numbers by IRAS. They are seen primarily at 60 and 100 μm and are distributed uniformly in the sky, but because of the high concentration of local objects in the galactic plane are studied mainly away from the plane. Roughly 20,000 galaxies, only half of which were previously cataloged, are included in Fig. 1. In the galactic plane itself, a large number of molecular clouds, identified as sites of star formation, are observed at 60 and 100 μm.

Many cool sources with color temperatures < 25 K are seen primarily, and often only, at 100 μm (8). These sources exhibit a coherent, almost connected, distribution on the sky and appear to be small structures within the much larger diffuse clouds of emission discussed below. They form one of the most surprising new aspects of the sky discovered by IRAS.

Large-Scale Extended Infrared Emission

The diffuse radiation at infrared wavelengths is a valuable source of information about the solar system, the Galaxy, and the early universe (9). Figure 2 shows the infrared sky brightness observed in a scan from the north to the south ecliptic pole (10). At wavelengths of 12 and 25 μm the sky is dominated by emission from interplanetary dust, which produces the broad peak of emission near the ecliptic plane. Zodiacal dust emission is also evident at 60 and 100 μm, but emission from the Galaxy becomes dominant at the longer wavelengths.

Emission associated with the solar system. Preliminary analysis of the interplanetary dust emission reveals several interesting properties of this sun-centered cloud and of the dust particles themselves. The infrared emission is surprisingly bright at all wavelengths, implying a substantial component of fairly large (diameter ~ 30 μm), dark (albedo ~ 0.1 to 0.2) particles. These characteristics are similar to those inferred from studies of scattered sunlight (11) and from micrometeoroid samples (12). The energy distribution toward the ecliptic poles is consistent with optically thin thermal blackbody emission at a temperature of 275 ± 60 K, although a model with 184 K grains whose long-wavelength radiative efficiency varies inversely with wavelength provides a comparably good characterization. These temperatures are lower than that of gray particles at 1 AU (13), suggesting silicate materials, which have high cooling efficiency in the infrared.

The variation of brightness at 12 μm with ecliptic latitude and longitude appears consistent with dust in a flattened disk-shaped distribution, in agreement with inferences from studies of visible zodiacal light (14). A clue to the dynamics of the interplanetary dust particles is the location of the symmetry plane of this distribution. The IRAS data show a brightness difference between the ecliptic poles which varies sinusoidally over the year and will provide an accurate means of measuring the inclination of the zodiacal cloud with respect to the ecliptic plane.

Emission associated with the Galaxy. Scans such as those in Fig. 2 show that at 100 μm the sky is consistently brighter on the side of the ecliptic plane closer to the galactic plane. This asymmetry implies the presence of a smoothly varying background arising from interstellar dust in the Milky Way (10). If the properties of this dust are similar to those of dust in the "cirrus clouds" discussed below, the preliminary study of the IRAS observations shows that the particles responsible for this smooth galactic background produce a visual extinction on the order of 0.1 magnitude toward the galactic poles. This is an important measurement because this extinction affects the cosmic distance scale (15, 16) and hence estimates of the expansion rate and age of the universe.

There is a tantalizing possibility that not all of the observed 100-μm brightness in Fig. 2 can be accounted for by

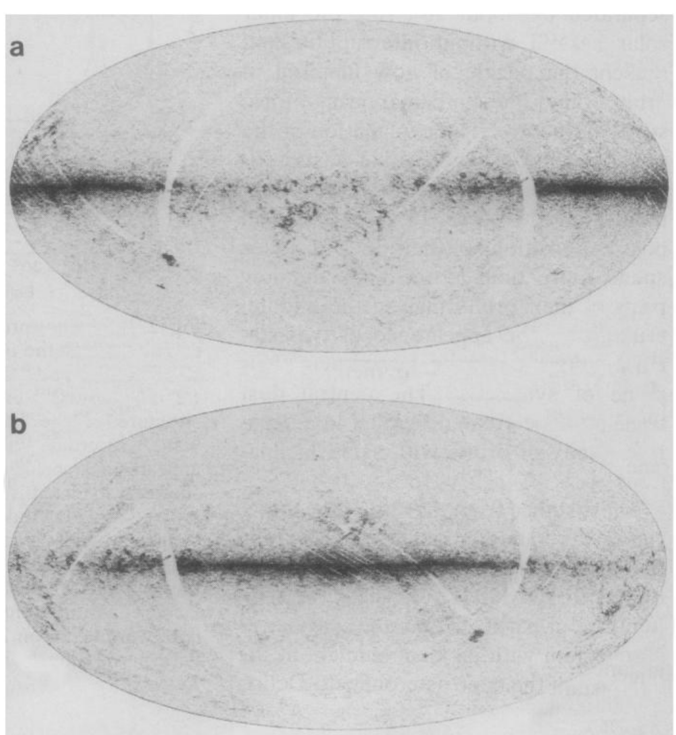


Fig. 1. Equal-area (Aitoff) projection of the inertially fixed point sources as seen by IRAS after the first sky survey, plotted in galactic coordinates. The center of the Galaxy is at the center in (a) and the anticenter direction is at the center in (b). The two largest gaps are areas covered with fewer than two hours-confirming layers at the end of the mission, although approximately half of those areas had single hours-confirmation coverage. The galactic plane, Magellanic Clouds, Andromeda galaxy, and Orion cloud complex are visible.

dust in the inner solar system or by normal interstellar dust. Additional potential sources of diffuse long-wavelength emission include cold material far out in the solar system and an extragalactic background of infrared radiation produced by the cumulative emission from distant galaxies. Examination of the IRAS data from the second half year of the survey should provide evidence for, or limits to, the existence of cold material within the solar system through its apparent shift in position (parallax). Identification of an extragalactic infrared background would contribute a missing component to the cosmic mass-energy accounting and valuable cosmological constraints on the early epochs of galaxy formation.

Medium-Scale Extended Infrared Emission

Zodiacal dust bands. IRAS has found unexpected features associated with the ecliptic plane which may be related to the origin of dust in the solar system (*17*). The features consist of a central band in the ecliptic plane flanked on both sides by parallel bands of emission. They are seen at all four wavelengths, with the greatest contrast relative to the underlying zodiacal emission at 25 μm. In Fig. 2 they appear as shoulders in the ecliptic plane emission. In Fig. 3 these features have been enhanced relative to the smoothly varying emission from the zodiacal cloud as a whole by spatially filtering the scans with a zero-sum high-pass filter.

These three parallel bands of dust, separated by about 10°, ring the inner solar system without interruption and present the puzzle of how material in orbit around the sun can appear to form such a structure. The explanation of the upper and lower bands is that dust particles confined to orbits with a fixed inclination—in this case 10°—but with all possible positions of their lines of nodes spend more time at the high and low parts of their orbits than in the middle, thus giving the appearance of two stationary bands running parallel to their plane of symmetry. The central dust band must be created by dust in a separate family of orbits with small inclinations.

The distance from the sun of the material in the bands, about 2.5 AU, can be deduced from the observed temperature of 165 to 200 K (*17*), close to the temperature of particles that are in radiative equilibrium with incident sunlight at the distance of the main asteroid belt. Debris from multiple collisions of asteroids is the probable origin of this material and may be an important source of interplanetary dust generally.

Infrared cirrus clouds. The 100-μm scans in Fig. 2 have a different character from those at shorter wavelengths; note the many hills and valleys on top of the underlying emission from the interplanetary and interstellar dust. These wispy clouds—infrared cirrus—are found in abundance even at the highest galactic latitudes, where the column density of interstellar material is expected to be at a minimum. There are at least two types of cirrus clouds, depending on whether they are positionally associated with known clouds of neutral hydrogen in the Galaxy.

At this early stage in the study of infrared cirrus it is clear that much will be learned about the interstellar medium, even though the possibility has not yet been ruled out that some fraction of these clouds may be in the outer solar system, at distances from the sun of only a few thousand astronomical units. Since both temperature and optical depth can be obtained for the brighter clouds, IRAS observations, when fully reduced and calibrated, can yield fundamental information about the nature of the interstellar material, its quantity, and its distribution. For example, from the high color temperatures observed—25 to 48 K—it is possible to conclude that very fine graphite particles must be a major component of these clouds. Further, the ratio of gas to dust must vary by at least a factor of 10 since some of the brightest and hottest cloud structures appear to be uncorrelated with observed gas clouds.

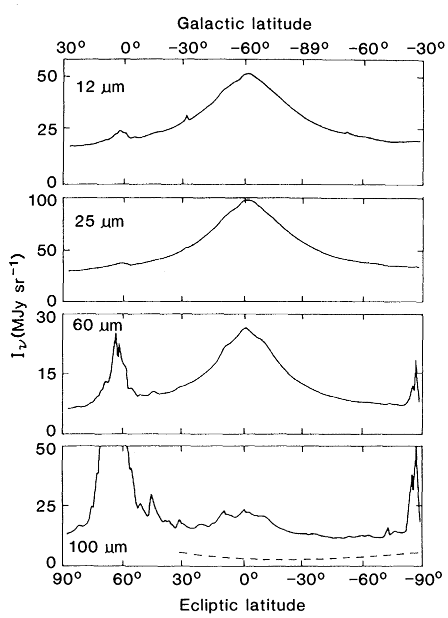


Fig. 2. Brightness profiles for a scan from one ecliptic pole to the other for each of the four IRAS bands. The data have been averaged to 1/2° resolution to emphasize the large-scale structure of the background. The ecliptic plane was crossed at a longitude of 1.3° and appears most prominent in the scans at the shorter wavelengths. The galactic plane was crossed at a longitude of 97° near the summer constellation of Cygnus and is brightest at the longer wavelengths. The dashed curve shows the estimated contribution of the smooth galactic emission component (see text). These data were taken on 24 June 1984. [Reprinted with permission from *Astrophysical Journal Letters*]

Figure 4 shows an example of a bright cirrus cloud associated with galactic neutral hydrogen located close to the south galactic pole. Based on estimates of the amount of dust in this cloud (*18*), a crude calibration can be made for the relation between the 100-μm brightness and the visual extinction, A_v. This leads to a typical value of 0.15 magnitude for A_v in the prominent clouds. As the image in Fig. 4 shows, the structure of these clouds is complex; if the distance to a cloud is 150 parsec (*19*), then the unresolved condensations have linear dimensions less than 0.1 parsec, whereas the cloud as a whole is more than 10 parsec in size. The origin, dynamics, and evolution of these nearby clouds of material, from which stars may someday form, are among the many challenging new areas of study made possible by IRAS.

Solar System Objects

One of the major results of IRAS is that comets are dustier than previously thought. The first comet discovered by IRAS came within 2 million miles of the earth—the closest approach of a comet in the last two centuries. Discovered independently by IRAS scientists and by Japanese and British amateur astronomers, comet IRAS-Araki-Alcock provided a close-up view of an object thought to be made up of the primordial stuff of the solar system.

IRAS observations of IRAS-Araki-Alcock (*20*) show emission from 250 K dust in an extended coma and a tail that extends more than 400,000 km away from the bright nucleus. This tail, which has no counterpart in the visual observations, requires a production rate of solid material of 200 kg/sec. This large amount of dust makes comets much brighter than expected in the infrared.

Considerable effort was expended at the quick-look data facility at the ground station in England to examine the satellite data daily in search of rapidly moving objects within the solar system. Bright seconds-confirmed objects that moved between hours-confirming sightings became candidates for follow-up observations by a network of ground-based optical telescopes. It was expected that near-earth asteroids would be detected frequently. Surprisingly, comets, not near-earth asteroids, were found at a rate of almost one per month. In all, five new comets, some visually as faint as 18th magnitude, and one Earth-crossing asteroid were discovered.

The Earth-crossing asteroid discovered by IRAS has been temporarily designated 1983 TB. It belongs to the Apollo class of asteroids and appears to be less that 2 km in diameter. It was first observed at a distance of 0.2 AU from the earth. Its orbit is almost exactly the same as that of the Geminid stream of meteoroids. Although 1983 TB looks like an asteroid in optical telescopes, the fact that debris from comets is thought to be responsible for meteor streams like the Geminids suggests that 1983 TB may actually be a dead comet whose ice and other volatile materials have boiled away during its many close passes by the sun.

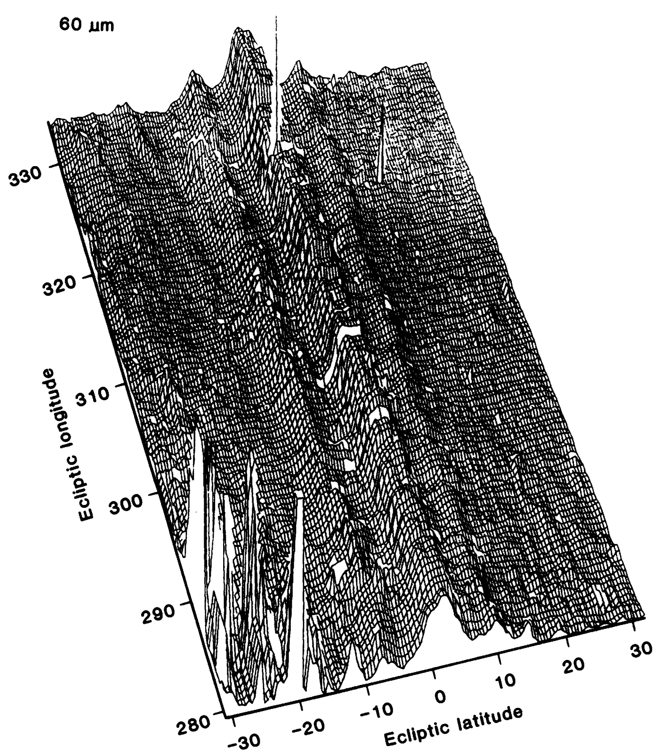
Solid Material in Orbit Around Nearby Stars

The IRAS calibration plan included special observations of several bright stars. One of these stars, Vega (α Lyrae) was discovered to be much brighter than expected at the longer infrared wavelengths (*21*). Vega, visually the fifth brightest star in the sky, is roughly 2.5 times more massive and 50 times more luminous than the sun and is classified as an A0V star.

Figure 5 shows the observed energy distribution together with that expected from the A0V star itself, a Rayleigh-Jeans tail of a 9700 K blackbody fitted to the observed flux at shorter wavelengths. The existence and magnitude of this excess (a factor of about 7 brighter than the star at 60 μm) is particularly surprising since Vega is a stable, isolated main-sequence star which has been extremely well studied and modeled at ultraviolet, optical, and near-infrared wavelengths and shows no signs of asymmetric or shifted spectral line profiles indicative of mass-loss processes.

The excess radiation is most likely due to thermal emission from solid material surrounding the star because (i) the energy distribution is reasonably well characterized by an 85 K blackbody spectrum and (ii) the emission source at 60 μm, while closely centered on the star, is noticeably extended with a size of about 20″. At the distance of Vega, 8 parsec (26 light-years), the measured angular size corresponds to a shell of radius 85 AU, the expected size of a shell of black- or gray-body particles in thermal equilibrium at a temperature of 85 K with radiation from the star. A surface area about 4000 times the surface area of the star is required to radiate the observed excess.

Because of the stable nature of Vega and the lack of any indication of mass loss that might result in formation of dust grains, it is assumed that the radiating material is in orbit about the star and has been present since approximately the time of its formation. The exact age of Vega is unknown, but the main-sequence



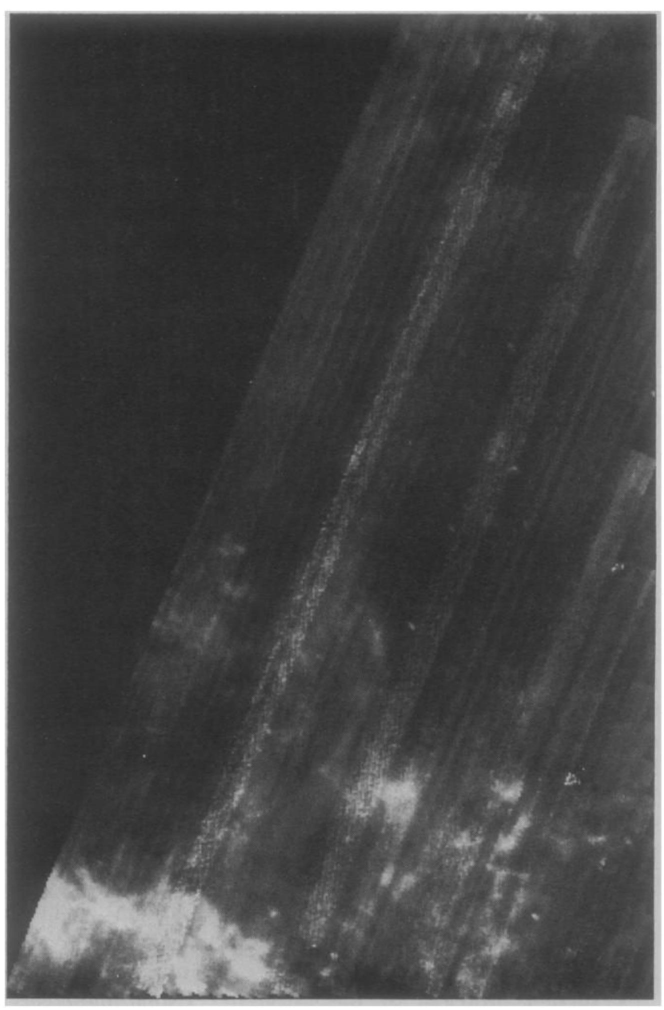


Fig. 3 (left). Zodiacal dust bands. IRAS data at a wavelength of 60 μm taken from scans across the ecliptic plane near 300° ecliptic longitude were spatially averaged to 1° resolution and high-pass filtered in the direction perpendicular to the ecliptic plane to show the zodiacal dust bands (see text). Intensity is proportional to the height of the projected three-dimensional surface. The three dust bands are found in the ecliptic and 10° above and 10° below the ecliptic, and run parallel to the ecliptic equator. The large peaks in the lower left of the map are due to the strong emission from the plane of the Milky Way. Fig. 4 (right). Infrared cirrus clouds shown by IRAS data taken at 100 μm. The bright cirrus cloud at the lower left is at right ascension ~ $1^h 3^m$ and declination ~ 6°50′ (1950). Fainter cirrus clouds can be seen over the rest of the field. North is up and east to the left in this field, which covers 16.5° of declination and 11° of right ascension with a resolution of 2 arc minutes.

lifetime of an A0 star is 3×10^8 years. Two arguments constrain the sizes of the particles. First, grains smaller than 20 μm will be blown away from Vega in only a few hundred years by radiation pressure. Second, orbital drag due to radiation pressure (the Poynting-Robertson effect) will, over 10^8 years, cause particles smaller than 1 mm in diameter to spiral into Vega.

We conclude that solid material larger than about 1 mm is in orbit about Vega. This is the first direct evidence for solid material much larger than interstellar grains (typically 0.1 to 0.5 μm in size) in orbit around a star other than the sun. Presumably this material is the result of the accretion and agglomeration of the residual gas and dust from which the star formed—the same processes thought to be responsible for the formation of our solar system. The IRAS observations provide neither indications of nor limits on the maximum size of objects in the Vega system. Observations at other wavelengths or by other techniques may be able to address this question.

IRAS has found unexpected far-infrared excess from several other nearby main sequence stars. Detailed observations of Fomalhaut (α PsA) give results qualitatively similar to those obtained for Vega. Data from several other nearby stars with evidence for cool rings are being analyzed. A preliminary analysis of IRAS survey data for about 100 nearby stars indicates that about 10 percent of the nearby main-sequence dwarfs exhibit an infrared excess suggestive of a cool ring or shell of material. Most of these stars are 2 to 5 times more massive and 5 to 100 times more luminous than the sun (spectral class A through F).

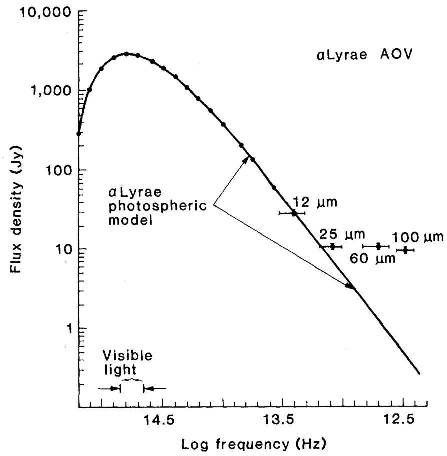


Fig. 5. Observed energy distribution of Vega and photospheric stellar model based on the observations in the ultraviolet, visible, and near-infrared. Notice the significant excess in the IRAS observations above the photospheric model, which indicates the presence of cold material around the star.

The Crab Nebula

The physical conditions in the Crab Nebula, the remnants of a star that exploded in the year 1054, were clarified by IRAS observations (*22*). From the radio to the ultraviolet, the dominant emission from the Crab is due to radiation from extremely energetic electrons moving in a weak magnetic field. These first far-infrared measurements of the Crab [upper limits had been reported (*23*)] imply a break in the spectrum at approximately 30 μm which, from synchrotron theory, requires a field strength of 300 microgauss and a maximum electron energy of 80 GeV.

A second property of the infrared emission from the Crab is the strong evidence for thermal emission from approximately 0.03 solar mass ($M_\odot$) of dust heated to 80 K by optical and ultraviolet radiation within the nebula. Although the exact amount of solid material present within the Crab is uncertain, it is considerably less than what is required if supernova ejecta are to be an important source of dust grains in the interstellar medium.

Star Formation

A major goal of IRAS is to understand how stars are formed. The current view is that stars are created by the fragmentation and collapse of interstellar gas clouds. These clouds, which consist of a few tens to a few millions of solar masses of molecular gas plus trace amounts of dust, condense under their own self-gravity or, possibly, under the influence of external pressures such as nearby supernovae. Infrared studies with ground-based and airborne telescopes (*1*) over the last decade have found that many molecular clouds harbor luminous sources of infrared radiation that must be hot young stars, 5 to 50 times more massive and up to 1 million times more luminous than the sun, which have formed within the molecular clouds and are still surrounded by the placental gas and dust.

Before IRAS, almost nothing was known about the early stages in the formation of low-mass stars—those like our sun—simply because of their faintness. IRAS can detect a star embedded in its parental molecular cloud, emitting 1 solar luminosity (1 $L_\odot$) to a distance of 500 parsec. Observations toward the nearby molecular clouds Barnard 5 and Chamaeleon I show that low-mass stars are forming in these small clouds of a few hundred solar masses (*24*). Three types of infrared objects have been found:

1) IRAS has detected compact, cool (< 25 K) clumps of gas and dust containing approximately 1.0 $M_\odot$ of material in both Barnard 5 and the Chamaeleon clouds. Some of these may be gravitationally unstable, that is, sufficiently dense and massive that the gravitational potential energy exceeds the thermal energy. Future far-infrared observations with greater spatial resolution will be required to set limits on the size and density of these clumps and to determine which are at the earliest phases of the formation of interstellar material into stars.

2) IRAS and ground-based (*25*) observations discovered a bright infrared source located within the dense core of Barnard 5 that emits 10 $L_\odot$ from 2 to 100 μm. The broad range of inferred grain temperatures (40 to 800 K) is consistent with heating by a bright embedded star. While the observations yield only the total luminosity of the object, a comparison with theoretical evolutionary models (*26*) suggests that an infrared object emitting 5 to 10 $L_\odot$ is the precursor of a 1-$M_\odot$ star that is still accreting material and contracting to the main sequence.

3) Associated with both clouds are infrared sources that emit about 0.1 to 0.5 $L_\odot$ in the IRAS bands with color temperatures of 200 to 250 K. The dust temperature and the presence of a visible star in a number of cases suggest that these are young stars that have moved away from the dense core from which they formed but are still enshrouded by dust that converts 5 to 20 percent of the visual output of the star into infrared emission. This idea is supported by measurements made with airborne telescopes, which showed similar amounts of far-infrared emission from T Tauri stars (*27*).

Examination of the IRAS survey will yield information about the rate of formation of solar-type stars within 1 kiloparsec and of more luminous stars across the entire Galaxy; about the relative lifetimes in different phases of the star formation process; and about the physical conditions that lead a molecular cloud to create new stars.

The Galactic Center

In the course of imaging the whole sky, IRAS has produced a map of the center of the Galaxy which has unprecedented sensitivity combined with moderate angular resolution and a wide field of view (*28*). The galactic center cannot be studied at visible wavelengths because it is obscured by large amounts of dust. Therefore all our knowledge of the central regions of the Galaxy has come from infrared and radio observations. The IRAS map extends previous infrared data by giving a broad view of the central Galaxy which reveals new details, especially in regions far from the well-studied central arc minutes of the nucleus. The wisps of dust extending out from the nucleus in Fig. 6 are structures first seen clearly in the IRAS data, as are the other bright filaments and wisps apparent all along the plane. This filamentary structure extends to the edge of this picture and beyond, merging with the infrared cirrus discussed above.

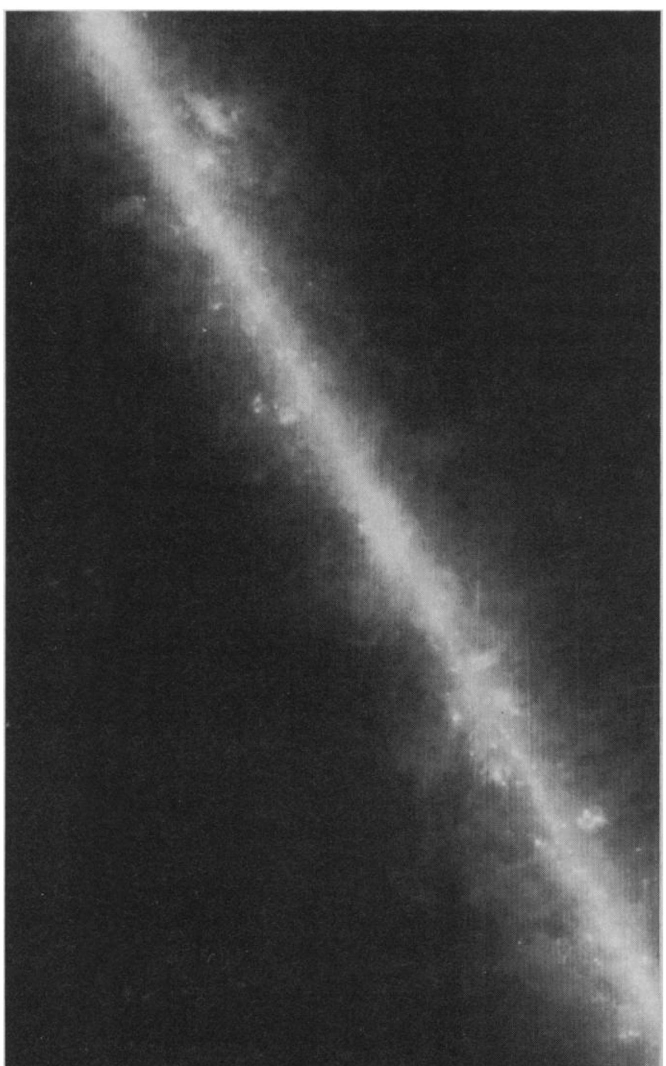
Extragalactic Objects

At 60 and 100 μm the brightest compact sources in directions away from the galactic plane are other galaxies. Before IRAS, only a handful of external galaxies had been measured in the infrared. IRAS has revealed that external galaxies have an enormously wide range of infrared activity. In some galaxies as much as 98 percent of the emergent radiation is emitted in the infrared, while in others the infrared luminosity is only a negligibly small fraction of the total.

Most of the infrared radiation is thought to be thermal emission by dust. It is commonly accepted that a large burst of star formation is occurring in galaxies that are moderately active in the infrared. Whether such a model can explain the extremely infrared-active galaxies discovered in the infrared-selected IRAS sample or the unidentified sources discussed below is not yet known.

The Andromeda galaxy. Figure 7 shows the Andromeda galaxy (Messier 31) as seen on visual photographs and as seen by IRAS (*29*). In the infrared, M31 looks like a flattened ring of emission with a central source that coincides with the nucleus of the galaxy. The ring corresponds to the inner regions of the optical disk and appears flattened because the disk of the great spiral is tilted out of the plane of the sky. The brightness of M31 rises steadily from 12 to 100 μm. This is typical of most normal galaxies, where the most important mechanism for production of infrared emission is the radiation of energy by dust particles heated by starlight; under typical interstellar conditions, dust grains are heated to temperatures of 20 to 30 K and radiate most effectively at wavelengths near 100 μm.

There is a close correspondence between the details of the ring structure and the pattern of dust lanes and regions of ionized hydrogen in the disk of M31. There is also a close similarity to images made from the radio continuum emission and from the 21-cm line of neutral hydrogen. This shows that the infrared emission probably comes from dust grains heated by newly formed massive stars, since the infrared flux is directly related to both regions with a high content of interstellar matter and regions inhabited by hot, young, highly luminous stars. The radiation from the nuclear source is a small fraction of the total infrared output from M31 and can be explained as emission from a small quantity of dust



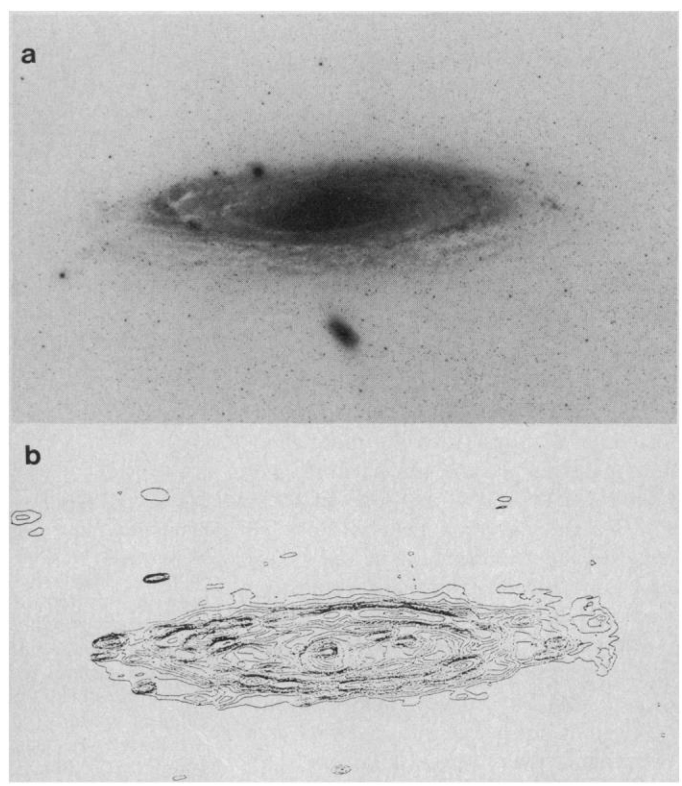


Fig. 6 (left). IRAS image of the central Galaxy in 60-μm light. Interstellar dust, concentrated in the plane of the Galaxy and heated by nearby stars, produces the bright band running from upper left to lower right. The nucleus itself is the large, prominent, bright knot in the center of the band. The other bright knots scattered along the galactic plane are ionized hydrogen regions and molecular clouds. This view covers about 48° of galactic longitude. North is up and east is to the left. Fig. 7 (right). Comparison of the appearance of the large spiral galaxy in Andromeda (M31) in (a) the visible and (b) the infrared. In the visual photograph the stars are dark and the dust lanes are light. In the contour plot of the infrared emission at 60 μm from the galaxy the dominant structure is the ring corresponding to the dust lane of the visual photograph.

heated by the old stars in the nucleus.

Visually bright galaxies. A study of a sample of about 100 of the visually brightest galaxies in the sky (*30*) shows that virtually all of the visually bright spiral and irregular galaxies (*31*), but none of the elliptical and very few of the S0 (or lenticular) galaxies have been detected by IRAS. The result is predictable since elliptical and S0 galaxies are more or less devoid of dust. M31, a typical spiral galaxy, is characteristic of the sample except that it is an extremely weak infrared emitter, with only 3 percent of its luminosity emerging in the infrared (*29*).

The visually bright spiral galaxies that IRAS has detected show infrared spectral energy distributions that rise from 12 to 100 μm. The percentage of the total energy from these galaxies that emerges in the infrared ranges from 10 to 85. It is most likely that the infrared emission from these galaxies arises in the same way as it does in M31—from dust particles heated by newly formed massive young stars. The temperature of the dust grains inferred from the ratio of the intensities at 60 and 100 μm ranges from 25 to 50 K. The level of the infrared flux emitted is a measure of the total number of hot young stars in the galaxy; clearly M31, at the bottom end of the distribution of infrared emission among these galaxies, is creating relatively few new, hot stars at this time.

In the sample of visually bright galaxies, there is a correlation (Fig. 8) between the ratio of the long-wavelength infrared intensity to the visible-light intensity and the 60- to 100-μm color temperature, in the sense that the more powerful infrared galaxies have higher temperatures. This can be related to star formation activity since the more luminous galaxies are the ones with higher total rates of star formation. In these galaxies the radiation field is more intense in the environment of the young stars, and the dust particles come to a high equilibrium temperature.

Visually faint galaxies. A photographic survey of the sky such as the Palomar Observatory Sky Survey (POSS) reveals many faint nonstellar images which can be recognized as external galaxies. IRAS has provided a new criterion for studying such galaxies, that is, those that are particularly bright at infrared wavelengths. Not surprisingly, galaxies selected from the IRAS survey on the basis of their brightness at 60 μm and subsequently identified with visually distinguishable galaxies show a significantly higher degree of infrared activity than do the visually brightest galaxies (Fig. 8). Since the distances to the galaxies are unknown, luminosities cannot be calculated; hence, the ratio of the infrared to visual luminosity serves as the measure of infrared activity.

For the 86 galaxies in the IRAS minisurvey sample (*32*), the ratio of infrared to visual luminosity ranges from 0.5 to 50, with a "typical" value of about 5. By comparison, the Galaxy emits roughly equally in the visual and infrared. While the galaxies found through their infrared emission are far more infrared-active than the visually selected galaxies, they are quite rare. A few percent of all galaxies have a ratio of infrared to visual luminosity of 2 or more, while only 0.05 percent of all galaxies have a ratio near 25—very rare galaxies indeed. When the morphology can be determined it is found that, as for the visually selected galaxies, only spiral or dusty galaxies are detected. However, more than one-quarter of the galaxies in the infrared samples are found to be peculiar or disturbed in form, or appear to be interacting with a near neighbor.

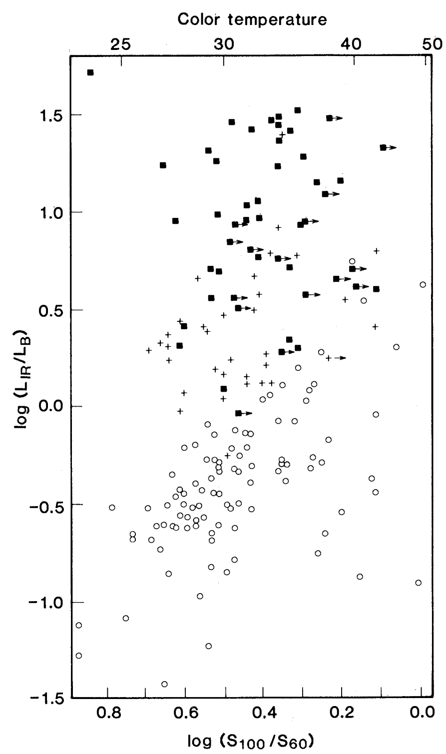


Fig. 8. The ratio of the far-infrared to visual luminosity plotted against the ratio of the flux at 100 μm to that at 60 μm for different samples of galaxies studied by IRAS. The ratio of infrared to visual luminosity is a measure of the relative infrared activity in the galaxy, while the ratio of fluxes in the 100-μm and 60-μm bands is proportional to the color temperature of the emitting material (*8*). The different symbols represent the different visual brightnesses of galaxies represented in the samples: (○) galaxies with visual magnitudes less than about 13, that is, those taken from the sample of bright visible galaxies; (+) galaxies from the infrared-selected sample with visual magnitude between 13 and 15; (■) galaxies from the infrared-selected sample that were previously uncataloged, that is, have estimated visual magnitudes between 15 and 18. The tendency for the ratio of infrared to visible luminosity to be correlated with the visual brightness of the galaxy is a selection effect, the result of the infrared flux–limited nature of the galaxy samples.

Unidentified sources. Perhaps the most intriguing sources found by IRAS at high galactic latitudes are those refered to as unidentified sources (*33*). Roughly 5 to 10 percent of the 60-μm sources at high galactic latitudes with the infrared flux ratios characteristic of the galaxies described above have either no visual images or only faint stellar-like images on the POSS at the infrared positions.

If these sources are galaxies, they must have ratios of infrared to optical luminosity larger than those of the bulk of the galaxies shown in Fig. 8. From the known flux density of these infrared sources and the upper limit on the brightness of any corresponding galaxy image, the ratio of infrared to visual luminosity must be larger than 40, which corresponds to the most extreme galaxies found in the infrared-selected sample.

Visual images have been obtained with large optical telescopes for ten such unidentified source locations (*34*). All but one show the presence of one or more faint galaxies. The one remaining field appears to be blank to a visual magnitude of +23, or roughly 100 times fainter than the limits from the POSS. Although accurate photometry is not available for the galaxies, the sources corresponding to galaxies appear to have ratios of infrared to visual luminosity in the range 50 to 150. Spectral data are not yet available for these galaxies, so there is no reliable estimate of their distance or total luminosities.

Clusters of galaxies. One of the factors that may influence the physical properties of galaxies is their environment. It is important to study the infrared properties of galaxies in clusters showing differing distributions of galactic types and densities. The initial IRAS study of galaxy clusters focused on the well-known spiral-rich Hercules cluster (*35*). Observations of the central 0.8 square degree of this cluster, to a sensitivity ten times deeper than the regular survey, led to the detection of a total of 41 sources at 60 μm. Of these, 30 can be identified with spiral galaxies on optical photographs and nine with stellar appearing (although possibly extragalactic) objects; two have no optical counterparts on the POSS.

The general properties of the galaxies found in this cluster do not differ drastically from those of the two large samples discussed above, with ratios of infrared to visual luminosity ranging from 0.2 to 5. In addition, in this relatively small field a number of unusual objects have been detected, including at least three active galaxies and a pair of galaxies undergoing a gravitational interaction. The most infrared-luminous galaxy in the sample, NGC 6045, shows evidence on optical photographs of a disk distorted by an interaction with a neighbor galaxy.

Active galactic nuclei. Many of the objects known collectively as active galactic nuclei, which include such classes of objects as radio galaxies, Seyfert galaxies, BL Lac objects, and quasars, are known to emit significant power in the infrared. These objects are characterized by one or more of the following general properties: spatially unresolved nuclei, broad optical emission lines, powerful x-ray emission, powerful radio emission, and rapid variability. The ultimate energy source for at least some of these objects is thought to be material accreting onto a massive black hole at the center of the galaxy. While in some cases, as in the Seyfert galaxies NGC 1068 and Markarian 231, the infrared luminosity dominates the output of the objects and is thought to be due to emission by heated dust, in many cases the mechanism responsible for producing the infrared emission is uncertain, and could be either thermal dust emission or electron synchrotron radiation. In these cases the infrared observations have been eagerly awaited.

Many Seyfert galaxies are quite bright in the infrared and have been observed in the IRAS survey, and the more extreme of the infrared-selected galaxies could represent a significant addition to this class. Unfortunately, the most luminous objects known, the quasars, are sufficiently distant that only a few tens of these objects are detectable in the IRAS survey. Only two quasars were bright enough to be observed at far-infrared wavelengths (*36*) before IRAS.

The radio galaxy 3C 390.3 is a well-known active galaxy which has been studied intensively at radio, optical, and x-ray wavelengths and is bright enough to be seen in the survey. Surprisingly, the energy distribution of this object, which was expected to show a smooth continuum throughout the infrared, shows a strong peak at 25 μm (*37*). In fact, the energy output of 3C 390.3 is largest in the infrared. The favored interpretation of the 25-μm peak is that it results from thermal emission from a region with a temperature of 180 K and more than ~ 200 parsec across. Although similar thermal components have been observed in some Seyfert galaxies, this is the first evidence for a thermal dust emission component in active radio galaxies.

Broadly speaking, "radio-quiet" and "radio-loud" quasars, which differ by a factor of ~ 100,000 in their relative radio output, have the same energy distributions from the x-ray through the visible and out to 10 μm. Although first discovered through their radio emission, most quasars are now thought to be relatively radio-quiet. There must be a sharp break in the energy distribution of the radio-quiet quasars at some wavelength between 10 μm and 1 mm. Why some quasars are strong radio emitters and others are not is not understood. In the first analysis of the IRAS data, three radio-quiet and three radio-loud quasars were selected (*38*). Qualitatively, they all show similar energy distributions rising from 12 to 100 μm, thus confining the discontinuity in the spectrum of radio-quiet quasars to wavelengths longer than 100 μm. However, the radio-quiet quasars may show an excess of 100-μm radiation relative to radio-loud quasars. This excess is tentatively identified as the signature of a spiral galaxy surrounding the radio-quiet quasars and may be the first evidence for generic differences outside their radio properties in these two types of quasars.

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