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Infrared Astronomy

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The major advances in our understanding of the universe have, in the past decade, almost all come about through the increased width of the electromagnetic spectrum open to the astronomers' scrutiny. Within the past ten years, the γ-ray, X-ray, far ultraviolet, infrared and millimeter wavelength parts of the spectrum have been added to the more traditional domains of optical and radio astronomy. Although the first celestial infrared observations date from Herschel in the eighteenth century, they were limited until recently to comparatively short-wavelength observations of solar system objects and bright stars. The development of new detection systems in the 1960's and the discovery of some unexpectedly bright celestial infrared sources led to a blossoming of interest in the subject both in the United States and in Europe. Several countries are now engaged in designing and building major new infrared facilities for use both at ground level and in space. Much of this activity is attributable to the well-founded hope that infrared observations will help to clarify two of the most interesting problems in modern astronomy, namely the interplay between the stars and the interstellar medium, and the origin of the powerful radiation emitted from the nuclei of certain galaxies.

Technical Developments

The Earth's atmosphere places severe restrictions on the types of terrestrial infrared astronomy possible. Between wavelengths of 1 μm and 40 μm there are several "windows" in the atmosphere through which infrared rays may pass without severe attenuation ; two of the most frequently used windows are those between 2.0 and 2.4 μm and between 8 and 13 μm. At these wavelengths, astronomers usually employ large ground-based reflecting telescopes and cryogenically-cooled solid-state photon detectors such as gallium-doped germanium bolometers or indium antimonide photovoltaic devices. A problem inherent to terrestrial infrared astronomy is the fact that any body at a temperature of about 300 K radiates very strongly at wavelengths of around 10 μm. Infrared telescopes therefore have to be specially designed to prevent radiation from their structure reaching the detector. A great deal of infrared astronomy however, has until now, been done using modified large optical instruments such as the Palomar 200-inch telescope.

Over the wavelength 40 μm - 300μm the Earth's atmosphere is almost totally opaque. To overcome this problem it is necessary to employ remote controlled balloon-borne telescopes or airborne observatories. An example of the latter is the gyro-stabilized 91-cm diameter infrared telescope which is fitted inside a C-141 jet transport aircraft and operated by NASA. Flights of eight hours duration at 41,000 feet enable astronomers to study infrared sources from above all but 0.1 % of the water vapour in the atmosphere which is the agent responsible for most of the absorption at these wavelengths.

At the longest infrared wavelengths, between 0.3 and 1.5 mm, infrared astronomy merges into radioastronomy; ground-based observations are again possible (from high, dry sites at least) and bolometers gradually give way to coherent radio receivers. Essentially the whole of the infrared spectrum, therefore, from radio to visible, has become accessible to astronomers during the past few years.

Infrared Sky

There is, at the moment, a severe shortage of adequate surveys of the infrared sky. The only unbiased catalogue is that of the Caltech group who, in 1969, listed the brightest 5000 sources in the Northern Hemisphere. This survey was performed at the comparatively short wavelength of 2.2 μm. There also exists a survey of much of the sky at 4 μm, 11 μm and 18 μm made by the U.S. Air Force using a rocket-borne telescope, but the reliability of this survey is difficult to

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assess because the technical details are still classified. A major revolution in infrared astronomy will hopefully take place in 1981, with the launching of a joint U.S./Netherlands/UK satellite named IRAS. This instrument is expected to detect about a million infrared sources at wavelengths between 8 μm and 300 μm.

At wavelengths shorter than 5 μm, most of the bright infrared sources are stars, mainly those with surface temperatures in the range 1500-3000 K, i.e. rather cooler than the 6000 K of the Sun. At wavelengths longer than 5 μm, the emission from normal stars becomes progressively fainter and other, quite different objects, dominate the sky. Some of these are old stars which are ejecting matter from their surfaces into interstellar space, but most lie in the spiral arms of our Galaxy, in the regions where new stars are believed to be condensing out of the interstellar medium. Extragalactic objects such as quasars, and the nuclei of certain galaxies are seen all over the sky but, in contrast to the situation at radio wavelengths, are considerably less prominent than the brightest galactic sources. Their intrinsic luminosity is, however, very much greater.

Interstellar Dust

There is no single emission mechanism responsible for celestial infrared sources. Some objects emit infrared radiation by virtue of the same processes as those responsible for other wavelengths. For example, the 1 μm-5 μm spectrum of most nearby visible stars is an extrapolation of their approximately Planckian energy distributions which generally peak in the visible range whereas the infrared emission from the Crab Nebula is mainly synchrotron radiation, as at radio, optical and X-ray wavelengths. The brightest and the most interesting infrared sources, however, depend on a different emission mechanism, namely thermal radiation from heated dust particles. The existence of interstellar dust grains was deduced many years ago from studies of the attenuation and reddening of the light from distant stars. The composition of these grains is still very uncertain, but several lines of evidence suggest that they consist of a core of refractory minerals such as magnesium silicate, covered by a mantle of solid methane, ammonia and ice. Graphite particles may also be present. The sizes and shapes of the particles are also uncertain, although it is thought that at least some have diameters of the order of 0.1 μm. Both the chemical composition and the size distribution of the particles may vary from one point in the Galaxy to another.

In most parts of the Galaxy the number density and the temperature of the interstellar grains is very low — of the order of one particle per 10^5 m^3 at a temperature of 10 K. The infrared emission from this source is too diffuse to have been detected yet. If the dust grains lie close enough to a star, however, they can be heated to temperatures of several hundred K. They then emit more strongly, especially at the more easily observable shorter infrared wavelengths. In some cases the hot dust is recognizable as an infrared "excess" in the energy distribution of the star, while at other times a region of extended emission, an infrared nebula, is seen.

For a cloud of dust to become a detectable infrared source it must not only be hotter than the average interstellar region, but also have a considerably higher space density of grains. Infrared sources therefore in general require some kind of association between a star and a dense region of the interstellar medium. Gas dynamical calculations show that simple gravitational accretion of the interstellar medium by a star is unable to account for such associations, so we must conclude that there is a generic connection between the star and the dust. Such a connection can arise in two ways ; either the star produces the dust or the star is produced out of the cloud which contains the dust. Both situations are, in fact, observed.

Mass Loss from Stars

It has been known for some time, from optical spectroscopy of stellar atmospheric gas velocities, that a wide range of different types of stars expel large quantities of matter into interstellar space. This material has an approximately cosmic elemental composition of about 70 % hydrogen, 30 % helium and 1 % for all the rest of the elements. As the material flows outwards, often driven by radiation pressure from the star itself, it cools, allowing solid particles to condense out. Under interstellar conditions the hydrogen and helium do not solidify, but most of the rest of the elements do. Dust grains, therefore, comprise about 1 % of the mass of the ejected gaseous material, as they do in the general interstellar medium. Although some hot, young stars are undergoing mass loss, the effect is much more important for stars in the late stages of stellar evolution. The loss may happen slowly, in the form of a steady wind from the surface of large cool stars, or suddenly, as in the explosions which give rise to novae and planetary nebulae. The return of mass from stars to the interstellar medium is of great importance for the evolution of the Galaxy since the matter that has passed through the thermonuclear processing in stellar interiors will have been enriched in heavy elements.

Birth of Stars

Stars are formed by the gravitational collapse of interstellar clouds. Broadly speaking, if the self-gravitational potential energy of a cloud of interstellar gas exceeds its thermal energy, the cloud will contract. The gravitational energy liberated by the collapse is at first radiated into space, but as the density increases, radiation is trapped in the cloud, causing its temperature to rise. The cloud is unstable and forms one or more hot dense cores which become the nuclei of future stars. As matter continues to accrete on to these cores, their temperatures and densities rise until thermonuclear reactions can start and the cores become fully operative stars. Objects in the intermediate stage between an interstellar cloud and a star are sometimes called "protostars".

The birth of stars is difficult to observe at visible wavelengths because the dust grains within the cloud obscure its central regions. Infrared observations are therefore valuable for two reasons. Firstly, infrared radiation penetrates dusty regions with much less attenuation than light, allowing us to study newly formed stars while they are still enveloped in the cloud in which they were born. Secondly, by searching for hot, dense regions in the cloud we may find the location of protostars which are still at an early stage in their formation.

Fig. 1 shows one such region of star formation, namely that associated with the Orion Nebula. The optically brightest part of the nebula is comprised of gas which is ionized by a cluster of hot stars that was formed some 10^5 years ago. Some infrared emission comes from the dust associated with the ionized gas, but most comes from a separate cloud which is behind the visible nebula, but cannot be seen at optical wavelengths. At the comparatively long infrared wavelength at which this map was made (λ = 100 μm) the emission is predominantly from the extended, cooler areas of dust. Maps at shorter wavelengths (around 10 μm) show that the centre of this extended cloud contains a compact cluster of hotter protostars. The temperatures and luminosities of

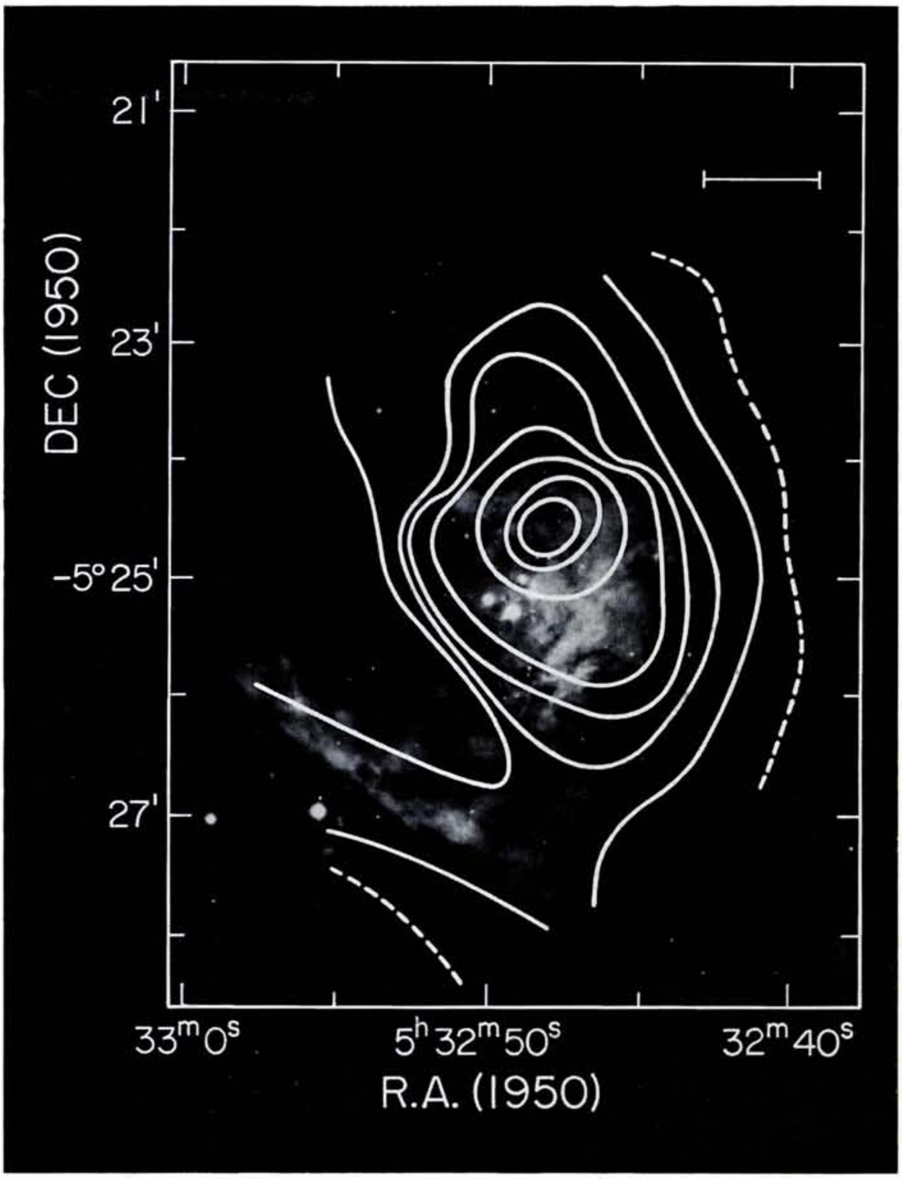

Fig. 1 The Orion Nebula by visible and infrared radiation. Contours of equal surface brightness of 100 μm emission are superimposed on a photograph of the Orion Nebula taken in red light. The infrared emission comes mainly from a warm cloud of gas behind the visible nebula. At the centre of the infrared cloud several young optically invisible protostars have been detected. Figure adapted from Werner et al. Astrophys. J., 204 *(1976) 420.*

these protostars indicate that they will probably evolve into stars similar to those which are ionizing the visible nebula in Fig. 1.

Several sites of star formation have been discovered and studied in the past few years by a combination of infrared, millimeter-wave and radio techniques. As yet, however, most studies have been of regions where large, very luminous stars are forming. Our understanding of the formation of small stars like the sun is still far from complete.

Nuclei of Galaxies

One of the most luminous infrared sources in our Galaxy is located at its nucleus. This source bears some resemblances to the star formation regions in the spiral arms, but may well be powered by a quite different mechanism. One speculation is that the luminosity is provided by the energy released as stars fall into the gravitational potential well of a massive black hole.

There exists in the universe a significant number of galaxies, perhaps 1 % of the total, which have infrared emitting nuclei at least 10^5 times more powerful than the nucleus of our Galaxy. Some of these galactic nuclei may be explicable by dust emission, but in some cases there appears to be another mechanism at work as well ; synchrotron radiation by electrons in a strong magnetic field is the most plausible explanation.

Infrared-emitting galaxies appear to be related generically to quasars and radio galaxies. A better understanding of how they work will therefore contribute not only to our understanding of large-scale physical processes, but also to the wider problems of cosmology and the origin of galaxies.