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The early days of infrared space astronomy

INTRODUCTION

Infrared observations can provide a number of unique perspectives on the Universe. This article concerns itself with the men and women who pioneered infrared space astronomy, traces the different techniques they employed, describes the trials and tribulations they had to overcome, and lists some of the gains they achieved. In the process it also examines the social institutions, both academic and military, that were most influential in determining the evolution of the field.

While many infrared and submillimeter observations required going into space, a large number of others were carried out from the ground. The earliest successes of infrared astronomy were largely the work of ground-based astronomers. Going into space required major technological breakthroughs that took time to materialize. A rich texture of sometimes friendly, occasionally aggressive, competition among ground-based, balloon, airborne, rocket, and satellite observers emerged, that persists to this day.

As an active participant in the field, the author makes no claims to objectivity. Nor is he able, in a chapter of twenty or thirty thousand words, to give proper credit to all who made significant contributions. The story told here is overwhelmingly based on personal experiences in the USA. Many of the struggles faced in the USA, however, were duplicated in Europe, Japan, and the Soviet Union. An excellent review written more than 20 years ago by J.E. Beckman and A.F.M. Moorwood (1979) may provide the reader with a complementary European perspective, and D.A. Allen's even earlier book adds an Australian's viewpoint (Allen 1975). The author hopes that contributions such as these may eventually be synthesized to produce a dispassionate, comprehensive, truly international, and perhaps more broadly incisive account.

The cold universe

Much of the Universe is cold. The wavelength, λ, at which stars, galaxies, and interstellar or intergalactic gases radiate is inversely proportional to their temperature, T (Figure 1). The peak emission tends to occur at $\lambda = 3700/T$ micrometers, where T is measured in kelvin (K). One micrometer is a millionth of a meter, traditionally called a micron and abbreviated to μm (or simply μ in the early literature of the field). Observations at infrared wavelengths from 1 to 1000 μm are thus uniquely sensitive to astronomical sources in the temperature range from ~3000 K to 3 K. These include the coolest stars, planets, and interplanetary dust, circumstellar and interstellar matter, and, at the longest wavelengths and coldest temperatures, the earliest known radiation emitted by the entire Universe.

A dusty universe

Interstellar dust – microscopic particles composed of ices, minerals, and common organic and inorganic materials – is abundant throughout the Universe. These particles obstruct a clear view of the cosmos at optical wavelengths. Fortunately, a cloud of dust that may be totally opaque in the visible or ultraviolet can be virtually transparent in the infrared. Thus,

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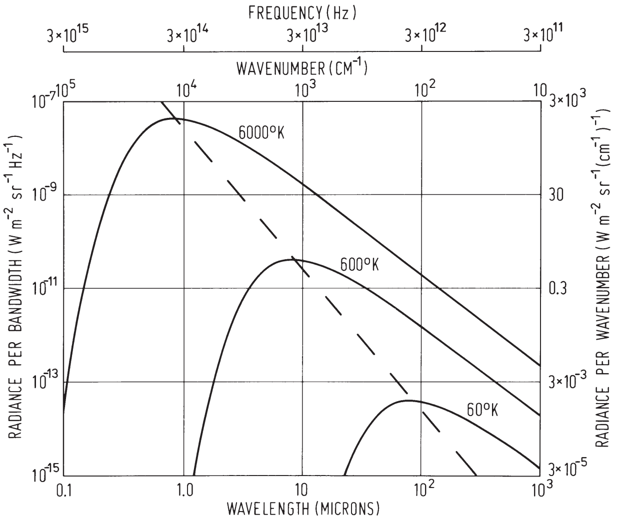

Figure 1 Blackbody radiation spectrum as a function of temperature. As the temperature *T* decreases by a factor of 10, the wavelength of peak emission increases by the same factor and the total power emitted over the entire wavelength range decreases by a factor of 10^4.

infrared wavelengths can probe regions deep in the core of a dusty galaxy that are inaccessible at shorter wavelengths.

Dust grains are heated by short-wavelength, mainly visible and ultraviolet radiation. They absorb this energy, and re-radiate it at infrared wavelengths. Because of this efficient conversion, the majority of the radiant energy emitted by dense, dusty regions, such as star-forming clouds and occasionally entire galaxies, lies at infrared wavelengths.

Since the transparency of dust clouds increases at longer wavelengths, red light is transmitted more readily than blue. Stars lying behind a tenuous dust cloud thus appear reddened. This reddening can be a useful measure of the amount of dust in the cloud.

The early universe

In the expanding Universe, the more distant an object the greater the velocity with which it recedes from us. This cosmic expansion shifts starlight from distant galaxies into the infrared region; the more distant the source, the farther is its radiation shifted into the infrared. The expansion is characterized by a redshift parameter, z, where $1+z$ gives the ratio of "wavelength reaching the observer" divided by "wavelength actually emitted in the distant source": $1+z=\lambda_{\mathrm{received}}/\lambda_{\mathrm{emitted}}$.

The most distant quasars and galaxies observed to date have redshifts $z>5$, so that radiation from the center of the visual band is shifted to beyond 3 μm. Because $1+z$ also represents the factor by which the Universe has expanded since the radiation was emitted, objects at $z=5$ are seen as they were at an epoch when the Universe was only one-sixth of its present size.

The chemical universe

The infrared band contains the spectral signatures of a variety of atoms, molecules, ions, and solids, at least some of which are found in any astrophysical environment. Infrared spectroscopy allows us to recognize large varieties of substances, ranging from cool ices in the interstellar medium to highly excited ions in active galactic nuclei. By determining the strengths of different spectral features, we obtain important, often unique insights into the chemical and physical conditions in these systems.

INFRARED ASTRONOMICAL CONSTRAINTS

The human eye ceases to respond to radiation beyond the red part of the spectrum. This limit falls at a wavelength of ~0.72 μm. The *infrared spectral domain* begins approximately at a wavelength of 0.7–1 μm, and stretches out to ~1000 μm (=1 mm). The wavelength range between ~200 μm and 1 mm is often called the *submillimeter domain*.

While the atmosphere tends to be opaque to much of the infrared spectral band, observations can be carried out from high mountain tops in a number of *atmospheric windows*. The lowest panel of Figure 2 shows the approximate widths and depths of the atmospheric windows at an observatory like Mauna Kea, Hawaii, sited at an altitude of 4.2 km. As seen from the upper panels, atmospheric absorption decreases and transmission increases considerably with increasing altitude, and becomes quite high throughout much of the infrared domain at aircraft and balloon altitudes, respectively, at ~14 and ~28 km.

For the astronomer, good atmospheric transmission is not enough. Low atmospheric emission is also essential. The atmosphere radiates powerfully throughout much of the infrared, and this emission is often orders of magnitude greater than the radiation from astronomical sources. The intensity of atmospheric emission also tends to fluctuate with time. In the near-infrared, at $1 \leqslant \lambda \leqslant 4$ μm, emission by OH radicals is highly variable. In the far-infrared, at around 100 μm, variable atmospheric water vapor content produces varying emissivity. Such fluctuations cause the flux, or *signal*, from an astronomical source to be marred by superposed *noise* due to randomly varying atmospheric emission.

Poor atmospheric transmission, and strong atmospheric emission are the prime reasons for undertaking infrared astronomical observations from space. However, in the early 1960s when serious efforts to conduct such observations were beginning, many of these factors were poorly understood. This led to parallel developments in infrared astronomy. Most astronomers worked with ground-based equipment taken to high mountain tops, while a few

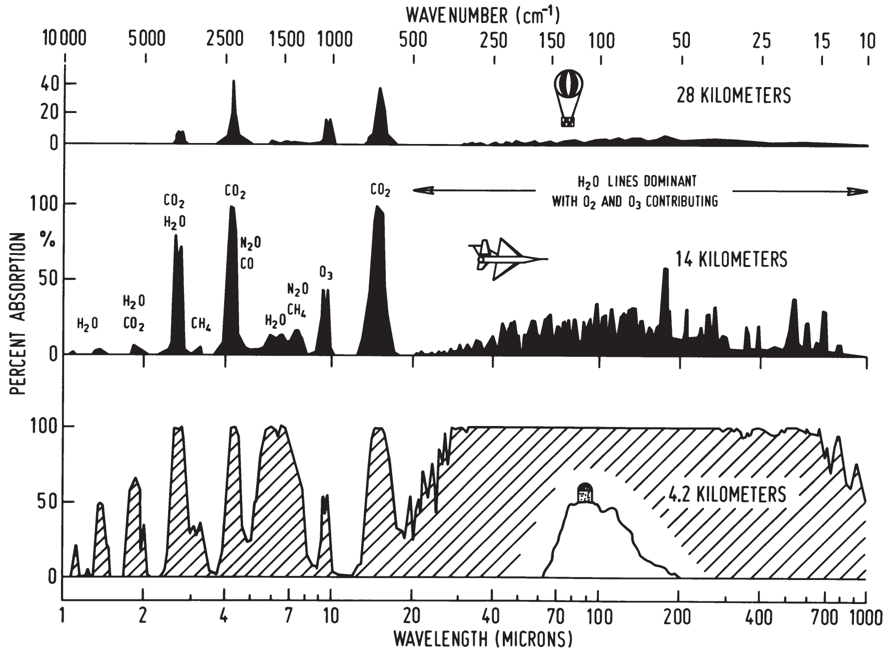

Figure 2 Atmospheric absorption in the infrared at altitudes of balloons, aircraft, and a mountain-top site like Mauna Kea (after Traub and Stier 1976).

attempted to build the instrumentation required to carry out observations from above the atmosphere.

Since rocket payloads were relatively expensive, US ground-based observers feared that the National Aeronautics and Space Administration (NASA) or National Science Foundation (NSF) support for rocket work would drain away funding from their own efforts. Uncertainties about the precise limitations of ground-based techniques often led to acrimonious disputes between ground-based observers and those who wanted to launch sensitive infrared astronomical telescopes above the atmosphere on rockets. Time and again, the more traditional astronomers bluntly recommended that rocket-borne efforts be slashed or pared back to an absolute minimum. Pioneering infrared rocket astronomy was not a happy venture!

To understand the backdrop against which the first successful observations were obtained, one needs to understand not only the technical difficulties that had to be overcome, but also the considerable early successes of ground-based observers who also had to surmount significant instrumental limitations but were able to make headway more quickly in more modest efforts.

EARLY GROUND-BASED EFFORTS

While the earliest attempts to conduct observations of astronomical sources beyond the red part of the spectrum date back to those of Sir William Herschel (1738–1822), who noted the thermal emission of the Sun beyond the visible spectral range, rapid progress did not occur until the 1960s. Two factors limited serious advances: a lack of sufficiently sensitive detectors and a lack of motivation.

In 1838 William Herschel's son John determined the total power emitted by the Sun. His results, obtained by measuring the rise in temperature of water in a blackened vessel on which was focused sunlight, were remarkably accurate given the simplicity of his apparatus. He found that the Sun radiated with enormous power. This posed a problem. Julius Robert Mayer's principle of conservation of energy, enunciated in 1845, led to the realization that the source of this energy had to be huge or the Sun very young, otherwise the Sun's energy would long ago have been depleted. Though many sought to resolve this puzzle, a satisfactory explanation did not emerge until the twentieth century and the development of theories of relativity and nuclear physics.

Thirty years after John Herschel's monumental finding, William Huggins used a thermopile connected to a galvanometer in the far more difficult attempt to measure the heat emitted by stars (Huggins 1869). (A thermocouple is a device consisting of strips of dissimilar metals that generate a voltage when one end of the device is heated.) These measurements were not particularly convincing, but Huggins's contemporary E.J. Stone developed the technique further (Stone 1870). He used two thermopiles back to back, alternating the positioning of a star first on one thermopile and then on the other, in a mode that we would today call "push–pull chopping" (Figure 3). He also calibrated his system against a radiating cube kept at the temperature of boiling water. With these steps he obtained more credible results.

Struggles to perfect increasingly sensitive instrumentation persisted. In the early decades of the twentieth century, pioneering work on better radiometers enabled W.W. Coblentz at the US National Bureau of Standards to report radiometric measurements of 110 stars, and a series of collaborations between Edison Pettit and S.B. Nicholson provided greater insights into planetary and lunar phenomena (Coblentz 1914, Pettit and Nicholson 1922).

The history of infrared detector development, however, was largely guided not by astronomers, but by military needs, such as "night vision" enabling warm objects to be discerned in the dark. World War II brought about the development of lead sulfide (PbS) cells that were far more sensitive than thermopiles. In the post-war era, Peter Felgett in Britain was one of the first to use these devices to measure the fluxes from bright stars (Felgett 1951). Later, the Cold War further accelerated military development of infrared sensors. One particularly successful detector, indium antimonide (InSb), came into use at wavelengths out to 5 μm. At longer wavelengths, the military was developing copper-doped germanium (Ge:Cu) and gallium-doped germanium (Ge:Ga) photoconductors. All these devices worked at their best only over a limited bandwidth, roughly $\Delta\lambda/\lambda \sim \frac{1}{3}$. To obtain continuous coverage over a broader bandwidth a succession of different detector materials had to be employed, each cryogenically cooled to its own optimum operating temperature.

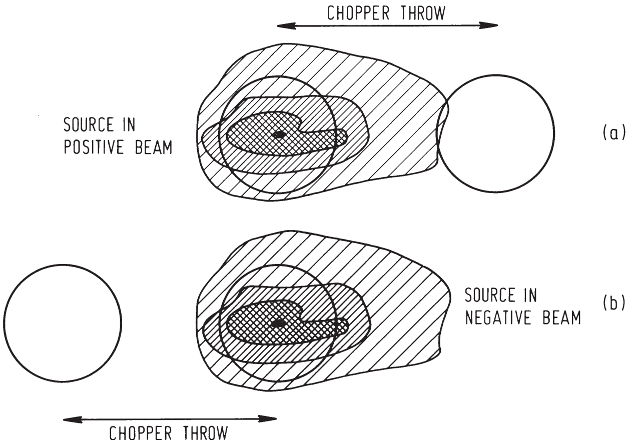

Figure 3 "Push–pull chopping" of a source by switching the field of view of the telescope between an astronomical source and its surroundings on two opposite sides. By subtracting the emission from the surroundings, a first attempt is made to correct for atmospheric emission above the telescope.

If an astronomer could secure a particularly sensitive and stable detector, it was possible to undertake novel infrared measurements. One observer who took good advantage of these detectors was Harold L. Johnson who, with various co-workers, pioneered the Ultraviolet–Blue–Visual–Red–Infrared (UBVRI) photometric system still in wide use. The *I* band lies at 0.9 μm. Johnson also made observations in the *K* band at 2.2 μm and at longer wavelengths. He set out to obtain accurate photometric data on several thousand bright stars and soon realized the importance of reddening and extinction by interstellar dust (Johnson 1965). The general attitude of his time, however, remained that infrared astronomy would continue to be merely an adjunct to optical work. Stars, after all, were known to be visible objects; and the Universe appeared to be largely an aggregate of stars.

Given the still-formidable technical difficulties, most astronomers found little motivation for embarking on a career in infrared astronomy.

This attitude changed with the work of Gerry Neugebauer and Robert W. Leighton at Caltech, who decided to conduct an unbiased survey of the sky at 2.2 μm, where the atmosphere is transparent and PbS is sensitive. Since the amount of observing time that would be required was great, and no telescope was available for the purpose, Leighton and Neugebauer constructed their own. Much of their inexpensive instrumentation was war-surplus, but the 1.57 m (62-inch), *f*/1 parabola they conceived was made from aluminum hollowed out on a lathe. The surface obtained in this fashion was not sufficiently accurate, so they poured a layer of epoxy into the paraboloid, spun it up around its vertical axis and kept it spinning until the epoxy had set. Properly coated, this gave a reflecting surface good enough to produce images of the order of 2 arc minute resolution. This was satisfactory, since their eight-element PbS array pairwise scanning the sky in a push–pull chopping mode would have to cover 30,000 square degrees. This meant that the beam employed would, of necessity, have to be sizeable.

To assure themselves of the performance of their apparatus, Leighton and Neugebauer cross-calibrated against stars already known from Johnson's work. But they also hoped to go further. They were no longer restricted to pointing at visible stars and might find sources that had no optical counterparts.

The final results of their survey were not to be published until the late 1960s. But while the work was in progress the two researchers and one of their students discovered a number of truly remarkable sources. A letter to the *Astrophysical Journal* (Neugebauer *et al.* 1965) broke the news. It was electrifying!

> The motivation for such a survey is to obtain an unbiased census of objects that emit in the 2.0–2.5 μm atmospheric window [which] might reveal many potentially

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