11 August 1967, Volume 157, Number 3789 SCIENCE

Infrared Stars

The interaction between stars and interstellar clouds produces "infrared stars" of two different kinds.

Harold L. Johnson

Do there exist cool stars which radiate strongly in the infrared region of the spectrum but are invisible even in the largest telescopes? This question has intrigued astronomers for a long time, but only recently have infrared observational data bearing on this matter become available.

The question of the existence of very cool stars is important because we astronomers think such stars would be one of the earlier stages in the process of stellar formation. It is now generally agreed that stars are very likely to have been formed from clouds of interstellar matter by a process of gravitational contraction. The temperatures of these clouds, in their original tenuous state, is very low, perhaps only a few degrees above absolute zero. If we hypothesize that, from these cold interstellar clouds, stars having temperatures up to 30,000° Kelvin and higher have been formed by gravitational contraction, then we must conclude that there is a stage in the course of this process at which the temperature of the prestellar masses is some 800° to 1000°K. Objects of this temperature radiate strongly in the infrared, but very weakly in the visible region.

Searches for Cool Stars

There have been several searches for "infrared stars"—stars which are bright in the infrared but faint at visible wavelengths. One of the justifications for these searches is the hope that, among the stars that are discovered, there will be a significant number of very cool protostars, prestellar masses in the process of gravitational contraction.

Thirty years ago, Charles Hetzler (*1*), working at the Yerkes Observatory, carried out a small search for infrared stars. He took photographs of selected regions of the sky, using filters to isolate two broad spectral regions centered at approximately 8500 angstroms, in the near-infrared, and 5500 angstroms, in the visible region. Hetzler found several stars which are brighter by as much as 9 magnitudes in the near-infrared than in the visible region. All of his reddest stars vary in brightness and very probably belong to the class of relatively cool, long-period variable stars whose prototype is the well-known variable Mira.

More recently, Haro and Chavira (*2*), working with the Schmidt telescope of the Tonantzintla (Mexico) Observatory, conducted an extensive photographic search for very red stars, at wavelengths of approximately 8500 and 6800 angstroms. They set themselves the condition that only stars which are brighter by at least 4 magnitudes at 8500 angstroms than at 6800 angstroms would be considered "infrared stars."

The Mexican astronomers found several thousand stars that are "infrared stars" by their criterion. They also used their Schmidt telescope to obtain low-dispersion, near-infrared spectra of these stars. A small-angle glass prism of aperture equal to that of the 26-inch telescope was placed over the upper end of the tube; this combination produced "objective prism spectrograms" for the stars within each 5- by 5-degree field. Haro and Chavira concluded that, with very few possible exceptions, the photographically discovered infrared stars belong to the class of relatively cool *M*-, *N*-, and *S*-type stars. Probably the majority are Mira-type stars. They carefully searched the regions of the sky where we already suspect young stars may exist, especially the Orion nebula region, and found no infrared stars which could be considered to belong to these very young clusters of stars.

Because of the use of photographic materials, photographic searches for infrared stars must be made at wavelengths shorter than about 1 micron (10,000 angstroms). It occurred to a group of astronomers at the California Institute of Technology (C.I.T.) (*3*) that a survey at a longer wavelength would be more likely to reveal very cool protostars. They designed and built an infrared telescope and photometer to scan the entire sky accessible from the Mt. Wilson Observatory. Their instrument, which includes a special lightweight, 62-inch "light-bucket," operates at two wavelengths, 2.2 microns (22,000 angstroms) and 8500 angstroms. The survey has been completed and articles identifying the reddest objects found have been published. Several of the infrared stars discovered by these observers are indeed extremely red; three have, according to measurements made in the University of Arizona's Lunar and Planetary Laboratory, the colors, over the wavelength range from 1 to 20 microns, which one would expect from a black body of temperature around 1000°K. One asks immediately whether these stars are the long-sought, low-temperature protostars. Unfortunately, the results of more detailed examination of the newly discovered infrared stars do not confirm this interpretation.

The author is research professor at The Lunar and Planetary Laboratory, University of Arizona, Tucson.

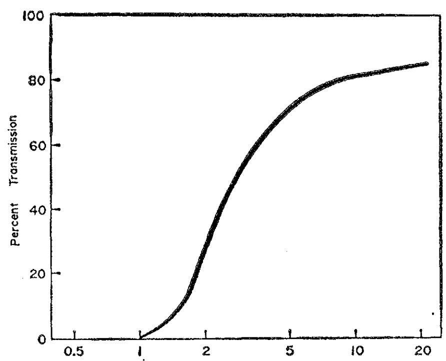

Fig. 1. Transmission of the interstellar cloud between CIT 11 and the earth. See also Table 1.

Two of the extremely red stars found by the C.I.T. observers are located in the constellation Cygnus, only a few celestial degrees from the extremely red VI Cygni association. (An association is a very loose, open cluster whose members usually are very hot stars. We know that the stars are hot because their spectra contain absorption lines corresponding to excitation temperatures of 10,000°K and higher.) One of these infrared stars in Cygnus, CIT 11, was measured by Wing and Spinrad (*4*) at the University of California, and its spectral type was found to be approximately FO I*a*. This notation indicates that the star is a supergiant having a temperature of approximately 7000°K; the determination is based upon the observed strengths of the near-infrared absorption lines of hydrogen, neutral oxygen, and singly ionized calcium. None of the molecular absorption bands that appear in the spectra of cool stars were observed.

The apparent black-body temperature of CIT 11 is about 2000°K, as compared with the actual temperature of 7000°K indicated by the spectrum. More than a dozen other stars in this same region of the sky, including those of the VI Cygni association, exhibit similar discrepancies between the apparent black-body temperatures and the actual spectrum-based temperatures. These discrepancies are known to be caused by the selective absorption of a dense interstellar cloud which lies between the earth and these stars; the effect is similar to that of the earth's atmosphere upon the sun's color at sunset, but much more extreme. The observed transmission curve of the interstellar cloud between CIT 11 and the earth, inferred from comparisons of the colors of CIT 11 observed in our laboratory with colors found for unreddened stars of the same spectral type, is shown in Fig. 1; the transmissions at several wavelengths are given in Table 1. The cloud is very opaque at short wavelengths, and it is obvious that an "interstellar filter" like this one will convert any star into an apparent infrared star.

Table 1. The transmission of the interstellar material between CIT 11 and the earth.

Wave-length (μ)	Trans-mission
∞	1.00
10	0.79
5	.69
3.4	.58
2.2	.31
1.25	.034
0.90	.0042
.70	.0002
.55	4×10^{-6}
.44	6×10^{-8}
.36	1×10^{-9}

The effects of this "interstellar filter" upon the brightnesses and colors of stars are illustrated in Table 2, for α Orionis (Betelgeuse) and for χ Cygni, a cool Mira-type variable, at minimum light. The effects of the filter upon magnitudes at infrared wavelengths are small, while the effects at visual wavelengths are very large. Indeed, the combination of two objects in the constellation Cygnus, χ Cygni and the very dense interstellar cloud, can produce an infrared star which is very bright in the infrared but invisible even in the world's largest telescope! The apparent black-body temperature of this hypothetical infrared star (which may, in fact, be representative of undiscovered objects in Cygnus, or elsewhere) is about 1000°K. Insertion of the "interstellar filter" between the earth and α Orionis would change α Orionis from one of the very brightest stars in the sky into a faint star invisible without the aid of a moderate-sized telescope, while affecting little the brightness at infrared wavelengths. It is quite clear that the very red colors of the newly discovered infrared stars are not sufficient to establish that they actually are extremely cool stars.

In both of the recent searches for infrared stars, that by Haro and Chavira and that by the C.I.T. group, it has been found that the infrared stars are strongly concentrated toward the plane of our galaxy, the Milky Way. Furthermore, Haro and Chavira found that the stars not only are concentrated toward the galactic plane but tend to be concentrated around the *edges* of the dense, dark nebulas in the Milky Way. From the observed distribution of infrared stars we infer a spacial relationship between these stars and the dark nebulas of the Milky Way; from the observation that the infrared stars are concentrated around the edges of the dark nebulas, not toward the centers of the nebulas, we infer that, on the average, the infrared stars are more distant than the dark nebulas and that the very high absorption in the centers of the nebulas prevents detection of the more distant stars. There is, on the other hand, a region around the edge of each dark cloud where the cloud material is sufficiently tenuous to permit detection of the distant stars but dense enough to produce highly reddened infrared stars. Distant stars which are not viewed through the edge of a dark nebula, being seen through the open spaces between the clouds, would be less likely to be reddened sufficiently for discovery as infrared stars.

It now appears that almost all (if not all) of the infrared stars that have so far been found by these two recent searches are stars of types which were already known, and that much of the extreme redness of these objects can be explained as due to reddening by interstellar matter. These searches have turned up a number of very cool Mira-type stars which certainly are the extreme cases of their type; they have also revealed several very highly reddened stars and have shown that the dark nebulas of the Milky Way are much more opaque than we had thought. These two discoveries have great significance in their respective fields, but they have not helped us in our quest for "true" infrared stars.

While the California Institute of Technology group, in their search at a wavelength of 2.2 microns, may well have found a few true infrared stars, which could be stars in the process of gravitational contraction, the number of such objects found is clearly so small, by comparison with the numbers of other objects found, that it is impractical to attempt to identify them. Another method of identifying possible candidates is needed.

Cool Stars among the Known Stars

All the evidence we now have points to a number of places in the sky where it seems likely there are stars in the process of formation. These are all regions where stars are plainly imbedded

Table 2. The effects of the "interstellar filter" upon the magnitudes of α Orionis and χ Cygni.

Star	Magnitudes		
	V* (0.55 μ)	K (2.2 μ)	N (10 μ)
α Orionis (observed)	0.42	−4.00	−4.76
α Orionis (with "filter")	13.92	−2.73	−4.46
χ Cygni (observed)	12.61	−1.34	−3.37
χ Cygni (with "filter")	26.11	−0.07	−3.07

* The brightest stars have visual magnitude V around zero; the faintest star visible with the unaided eye is about $V = 6$; the faintest star visible with the largest telescope in the world, the 200-inch on Palomar Mountain, is about $V = 21$. By definition, magnitudes V, K, and N are equal for a star of temperature 10,000°K.

in, and illuminate or excite, fairly dense clouds of interstellar material. Many have one or several very hot, very young, O-type stars intimately associated with the bright nebulosity. The best-known example is the great nebula in Orion, but there are several such regions which astronomers have studied intensively.

Among the fainter stars which we find in such regions are certain peculiar "nebular variables"—stars which are intimately associated with the interstellar nebulas and which vary irregularly in brightness. Many are "flare stars"—stars which can, in only a few minutes or even seconds, brighten by as much as 2 or 3 magnitudes and which then slowly return to their original brightness. Others are the "T Tauri" stars, so called after T Tauri, a peculiar star in the great clouds in the constellation Taurus. The spectra of these objects have bright emission lines and other features suggesting the presence of circumstellar clouds or shells. It is now a generally accepted theory that the T Tauri stars and flare stars in young clusters are stars in the process of gravitational contraction and that they have been formed from the interstellar clouds with which they are so intimately associated.

A Mexican astronomer, Arcadio Poveda (*5*), has presented arguments showing that at an early stage in the formation of the solar planetary system the material from which the planets were formed must have been distributed in a spheroidal circumsolar nebula. Nothing in Poveda's arguments seems to pertain uniquely to the sun; in fact, one would expect that all stars, when condensed, would be surrounded by compact "left-over" nebulas which could develop into planetary systems. Poveda advanced his theory as a possible explanation of the T Tauri stars and other nebular variables.

At this very early stage in the development of a star and its planetary system, the preplanetary mass would be distributed in a spheroidal circumstellar cloud. The cloud would consist of relatively small particles (perhaps 1 to 20 microns in diameter) and would be almost completely opaque to visible light. It can be shown that the mass contained in our own planetary system is sufficient, if broken up into small particles and spread out into a uniform circumsolar cloud, to obstruct almost completely the total energy output of the sun. Thus, most of the energy output of a developing star (which could have a temperature similar to that of the sun) would be absorbed by the circumstellar cloud; the absorbed energy would heat the cloud, and the cloud would reradiate the energy at long infrared wavelengths. Depending upon circumstances, the circumstellar cloud could radiate much as a black body having a temperature of 400° to 800°K does. At this stage, the developing star and preplanetary cloud would be a "true" infrared star of the type for which we have been searching.

Poveda predicted that T Tauri, R Monocerotis (the star at the head of Hubble's variable nebula), and similar stars might be very bright in the infrared, due to the presence of infrared-emitting components having temperatures perhaps as low as 400°K. From arguments given above it appears that the infrared-emitting components would be circumstellar clouds—preplanetary systems. He also suggested that, if the existence of these infrared components should be confirmed, we would also have shown the high frequency of planetary systems in solar-type stars.

Another Mexican astronomer, Eugenio Mendoza V. (*6*) (while a visiting astronomer at the Lunar and Planetary Laboratory, University of Arizona), measured the brightness of T Tauri, R Monocerotis, and other, similar stars at wavelengths ranging from the ultraviolet to 5 microns. He found that, as predicted by Poveda, these stars all have large infrared "excesses"—that is, they are much too bright in the infrared for agreement with their observed spectral types. In the visible region, T Tauri stars exhibit spectral lines indicating temperatures near that of the sun, or somewhat lower; the observed colors and brightnesses in the infrared, however, correspond to much lower temperatures.

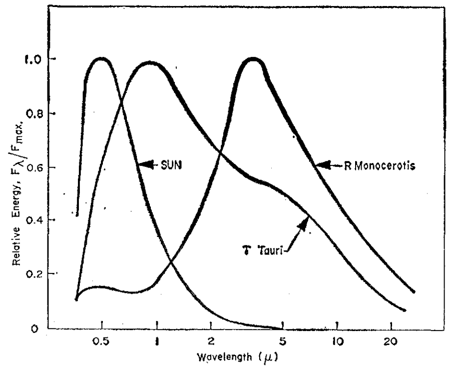

Fig. 2. The spectral-energy curve for the sun, T Tauri, and R Monocerotis. T Tauri illuminates NGC 1555 (Hind's nebula); R Monocerotis illuminates NGC 2261 (Hubble's variable nebula).

Two of these objects, T Tauri and R Monocerotis, were measured at a wavelength of 20 microns by Frank Low (*7*) of the Lunar and Planetary Laboratory. Most interesting is R Monocerotis, whose observed spectral-energy curve is shown in Fig. 2, along with curves for T Tauri and, for comparison, the sun. It is evident that almost all of the energy of R Monocerotis is radiated in the infrared and that this infrared radiation does not accord with the approximately solar-type spectrum found in the visible region.

One can explain the observed spectral-energy curve of R Monocerotis by hypothesizing a dense circumstellar dust cloud which absorbs almost all of the energy output of the star (whose temperature would be about 6000°K) and reradiates it at long wavelengths. Low and Smith showed that the observational data accord with the radiation expected from a circumstellar cloud of dust particles approximately 10 microns in diameter. About one-quarter of the mass of our planetary system would suffice to produce this phenomenon. The far-infrared observations for R Monocerotis and other T Tauri stars, and their theoretical explanation, are very important, for they do suggest that a great many, perhaps most, solar-type stars may have planetary systems.

Conclusion

Our searches for very cool stars have revealed three kinds of objects: very cool Mira stars, perhaps cooler than any of this type previously known; extremely dense interstellar clouds, more dense than any known heretofore; and, probably, cool circumstellar clouds that may be planetary systems in an early stage of formation.

The work on infrared stars has shown that the dark nebulas of the Milky Way are indeed extremely opaque. In fact, some of the clouds absorb so much of the light of the stars beyond that we would consider them to be completely opaque, for all earthly purposes. And there is every reason to suppose that even denser interstellar clouds are yet to be discovered.

Not only do the dark nebulas of the Milky Way obstruct our view of the distant stars but we have reason to believe that, given propitious circumstances, they can be the spawning places for stars. In an early stage of their development, young stars are imbedded in the interstellar matter from which they were born and are surrounded by "left-over" circumstellar clouds which in time will become planetary systems. If our interpretations are correct, a large percentage of solar-type stars have planetary systems; perhaps some of them are similar to our own.

References and Notes

1. C. Hetzler, *Astrophys. J.* **86**, 509 (1937).
2. G. Haro and E. Chavira, cited by H. L. Johnson, E. E. Mendoza, and W. Z. Wísniewski, *ibid.* **142**, 1249 (1965); see also *Bol. Obs. Tonantzintla y Tacubaya*, in press.
3. G. Neugebauer, D. E. Martz, R. B. Leighton, *Astrophys. J.* **142**, 399 (1965); B. T. Ulrich, G. Neugebauer, D. McCammon, R. B. Leighton, E. E. Hughes, E. Becklin, *ibid.* **146**, 288 (1966); E. E. Becklin and G. Neugebauer, *ibid.* **147**, 799 (1967).
4. W. Z. Wísniewski, R. F. Wing, H. Spinrad, H. L. Johnson, *ibid.* **148**, L29 (1967).
5. A. Poveda, *Bol. Obs. Tonantzintla y Tacubaya* **4**, 15 (1965); *ibid.*, p. 22.
6. E. E. Mendoza V., *Astrophys. J.* **143**, 1010 (1966).
7. F. J. Low and B. J. Smith, *Nature* **212**, 675 (1966).

Paleopathology: Meeting Ground for Many Disciplines

Ellis R. Kerley and William M. Bass

Paleopathology is the study of prehistoric disease and, as such, deals predominantly with skeletal remains and prehistoric populations. In its broadest sense, paleopathology deals with diseases in animal as well as human tissues, and consequently it is a field of interest to many scientific disciplines. When infection, malfunction, or trauma affect bones and teeth, the lesions or other abnormalities can be observed and studied, and in many cases the cause can be identified.

Evidence of disease in prehistoric populations is obtained from (i) human and animal remains and (ii) prehistoric art. In the literature there are various reports of abnormalities in the bones of prehistoric animals, but the first serious controversy involving possible abnormality in a prehistoric human specimen occurred in 1896 when the eminent German pathologist Rudolf Virchow questioned the authenticity of the Neander Valley specimen, and of Neanderthal man as a human fossil population, and suggested that the Neanderthal specimens were the remains of abnormal modern men (*1*). From that time on, attempts to detect and interpret abnormalities in prehistoric specimens have increased, and in recent years the methods of investigating prehistoric disease have become more complex as new techniques have been developed. The publication in 1923 of Moodie's monumental treatise on the subject (*2*) was a milestone in paleopathology. An equally important contribution was Ruffer's study of disease among the ancient Egyptians (*3*), wherein he introduced the microscopic study of lesions in mummified tissue. Other authors have dealt with specific populations or diseases; Hooton (*4*), for example, dealt with the Pecos Pueblo, and Herbert Williams (*5*), with syphilis in the New World. Virchow himself was interested in the possibility of detecting prehistoric disease, despite his declarations against the authenticity of Neanderthal man. In the United States one of the eminent champions of paleopathology was Aleš Hrdlička.

Since knowledge of the diseases, abnormalities, and epidemiology of prehistoric populations can shed light on hereditary relationships, on the adaptation of populations to disease environments, and on the times and routes of migration of peoples during prehistoric times, it is small wonder that anthropologists have long been interested in this field. Since not only skeletal material but disease itself is the subject matter of paleopathology, many disciplines find a meeting ground in these studies.

Information That Can Be Derived from Paleopathology

Examination of individual skeletons can yield an indication of abnormalities, tumors, malformations, fractures (in particular, healing or healed fractures) (Fig. 1), and other skeletal pathology. One can document the number of skeletal abnormalities in any given population, keeping in mind the fact that not all disease is skeletal and that not all members of a population are found in any archeological site. Sometimes it is not possible to identify the disease even when the skeleton shows obvious abnormality. One cannot distinguish between severe infectious processes of relatively short duration, but it is usually possible to distinguish between infection, disturbances of growth, and simple reparative processes. It is almost always possible to distinguish between major categories of lesions, such as uncomplicated injury and infection. It is possible to distinguish between infections (Fig. 2), malformations (Fig. 3), tumors, metabolic disturbances, and the like. Though there are exceptions, usually a specimen can be assigned to a major disease category. Not infrequently the causative factor of a particular type of lesion

Dr. Kerley and Dr. Bass are, respectively, associate professor and professor of physical anthropology at the University of Kansas, Lawrence.