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INFRARED PHOTOMETRY AND THE DETECTION OF CIRCUMSTELLAR DUST

Robert F. Wing
Department of Astronomy, The Ohio State University

RESUMEN

La presencia de granos de polvo en envolventes circunestelares de muchas estrellas, es conocida principalmente por su efecto en distribuciones de energía infrarroja. El desarrollo temprano de la fotometría infrarroja de banda ancha fue motivado por el deseo de mejorar la escala de temperaturas efectivas para estrellas frías y para estudiar la ley de enrojecimiento interestelar; el fenómeno del polvo circunestelar complicó considerablemente esos dos esfuerzos. Con el uso de anchos de bandas más angostos, la emisión de granos circunestelares se volvió un tema de estudio interesante, pues se encontró que los granos alrededor de estrellas ricas en oxígeno y ricas en carbón tienen rasgos espectrales distintos. Los datos del Espectrómetro de Baja Resolución de *IRAS* han permitido clasificar varios miles de cascarones circunestelares de acuerdo a su espesor y a la química de los granos.

ABSTRACT

The presence of dust grains in the circumstellar envelopes of many stars is known primarily from their effect on infrared energy distributions. The early development of wideband photometry in the infrared was motivated by a desire to improve the effective temperature scale for cool stars and to study the interstellar reddening law; the phenomenon of circumstellar dust complicated both of these efforts considerably. With the use of narrower bandpasses, the emission from circumstellar grains became an interesting subject of study in itself, as the grains around oxygen-rich and carbon-rich stars were found to have different spectral signatures. Data from the *IRAS* Low-Resolution Spectrometer have allowed several thousand circumstellar shells to be classified according to thickness and grain chemistry.

Key words: **HISTORY AND PHILOSOPHY OF ASTRONOMY — INFRARED: GENERAL — CIRCUMSTELLAR MATTER — DUST, EXTINCTION — TECHNIQUES: PHOTOMETRIC**

1. INTRODUCTION

Over a span of about five years in the mid-1960s, infrared wideband photometry developed from its infancy) the maturity of a technique that was counted on to provide basic data in a wide range of astrophysical pplications. In this heady development —which led to surprising discoveries as well as to the establishment of practical, general-purpose technique— several Mexican astronomers played key roles. In particular, Eugenio [endoza was the first to apply the methods of infrared multicolor photometry to several interesting classes of ars. I have to believe that Dr. Mendoza's involvement in the early days of infrared photometry was one of e most satisfying and enjoyable phases of his long and varied career.

Subsequently, infrared photometry has become such an established part of observational astronomy that it hard to think of areas of study that do not make use of it. Some of its current applications, especially those ertaining to the early stages of star formation, are discussed by others at this Symposium.

This paper has two parts, one historical and one more current. In the first, I will trace the development of e standard wideband system of infrared photometry from its beginnings around 1962 to its rather awkward success, five years later, in revealing the presence of dust in the circumstellar envelopes of stars of many commc types. This will not be a complete history, but only the biased account of one individual who, as a studen followed this development with great interest; by telling this story I will have an opportunity to recall one of tl exciting episodes in the history of 20th century astronomy and to point out a number of important contributioı that were made here in Mexico. The choice of the detection of circumstellar dust as the stopping-point of n story was made partly for expedience but primarily because it marked a real turning-point in the developmeı of infrared photometry, clearing up some of the puzzling results obtained earlier and at the same time openir up a new area of research —*viz.* the study of the dust itself. The second part of the paper is a sequel to tl first, describing what we have learned about circumstellar dust from subsequent observations, primarily thos obtained with the *IRAS* satellite.

2. DEVELOPMENT OF WIDEBAND INFRARED PHOTOMETRY

The filters used for wideband astronomical photometry at wavelengths beyond one micron are often thougl of as forming a single photometric "system," associated primarily with the name of Harold L. Johnson. Bı unlike the earlier six-color system of Stebbins & Whitford (1943), the *RI* system of Kron & Smith (1951), (the *UBV* system defined by Johnson & Morgan (1953), the infrared photometry did not originate all at onc and it was not introduced to the astronomical community via a single publication. Rather, its origin was more complicated, albeit rapid, development involving several individuals, instruments, and observatories. Heı I will trace this development, mentioning the objectives that motivated this work and some of its early result

2.1. Origin of the Standard Infrared System

When the decade of the 1960s began, very few measurements of objects outside the solar system had bee made at wavelengths beyond about 1.1 μm, the effective limit of both photographic emulsions and photoemissi devices. Whitford (1948, 1958) had measured a few stars at effective wavelengths of 1.2 and 2.1 μm for tl purpose of extending the interstellar reddening law, but apart from the pioneering work of Fellgett (1951), whic was not pursued, no systematic effort to collect stellar data at these wavelengths had yet begun.

In reviewing the photometric systems then in existence, Johnson (1963) pointed out that the combinatic of his *UBV* system with the *RI* system of Kron and collaborators would produce a five-color system that "directly competitive" with the six-color system of Stebbins & Whitford. Although this competition nev materialized, several observatories responded to Johnson's suggestion by building *UBVRI* photometers so th all five bands could be measured with a single detector. To do this, it was necessary to redefine the *U*, *B*, ar especially *V* filters to compensate for the change in sensitivity function of the detector. Today, most *UBVF* photometry is done with a single photometer and photocell (see, e.g., Fernie 1974; Bessell 1976).

Johnson's first efforts to extend stellar photometry further into the infrared were thus a logical extensic of his suggestion of combining *UBVRI* photometry into a single system. The first measurements in the *K* (2 μm) and *L* (3.5 μm) bands were reported in 1962 (Johnson 1962), the first at *M* (5 μm) the following ye (Johnson & Mitchell 1963), and the first at *N* (10 μm) one year later (Wildey & Murray 1964; Low & Johnsc 1964).

References to papers introducing the various infrared filters are collected in Table 1. There is no separa a paper introducing the *J* band (1.25 μm), although observations in *J* are included in early compilations photometric data (e.g., Johnson 1964), and Johnson (1962) had the *J* filter in mind when he named the other Apart from the *H* filter (1.65 μm) which was introduced later (see below), the filters beyond the *I* band aı named alphabetically in order of wavelength, starting with the first letter after *I* and continuing through *N*

Table 1. Papers Introducing Infared Filters

Filter	Wavelength	First Reported Use
K	2.2 μm	Johnson (1962)
L	3.5	Johnson (1962)
M	5	Johnson & Mitchell (1963)
N	10	Wildey & Murray (1964) Low & Johnson (1964)
H	1.65	Mendoza (1967)

ı the literature one can also find occasional mention of O, P, and Q filters in the 10–20 μm region, but these ave never been widely used or considered a 'part of the standard system.

When we look today at the papers cited in Table 1, we are likely to be surprised that infrared photometry as in such an infantile state only 30 years ago. These papers do little more than report detections of some f the brightest stars in the sky. The first observations at 10 μm were made with two of the world's largest elescopes —Wildey & Murray used the 200-inch on Mt. Palomar, while Low & Johnson used the 82-inch at [cDonald Observatory— and their measurements for stars observed in common show typical differences in the)–30% range. We should remember, of course, that this was before the days of IR-optimized telescopes and ıopping secondaries; in fact, astronomers were just starting to find out what it takes to do infrared photometry. he early bolometers and their cryogenic systems were not easy to use. But probably the biggest impediment) doing accurate photometry in those days was the complete lack of standard stars, without which it is very ard to know if one's detector is stable.

Johnson built his first infrared photometer at McDonald Observatory in Texas and put it into operation ı January 1961 (Johnson 1962). A short time later he moved to Tucson to join the Lunar and Planetary aboratory of the University of Arizona. It was during this period that he developed his close association with [exican astronomy, which was to last until his death in 1980. His first major compilation of stellar photometry ı the infrared (Johnson 1964) was published in the *Boletin de los Observatorios Tonantzintla y Tacubaya*, and collaboration between the Lunar and Planetary Laboratory and the Tonantzintla Observatory resulted in the ublication, two years later, of a large compilation of bright-star photometry (Johnson et. al. 1966), which ıcluded observations from U to L by Iriarte and Mendoza with the Tonantzintla 1.0-m telescope. Johnson was so involved in the selection of San Pedro Mártir as the site for the National Astonomical Observatory and ter arranged for the University of Arizona's 1.5-m photometric telescope to be moved there.

2.2. Early Applications

Applications of wideband infrared photometry in the mid-1960s fell mainly in two categories: (1) general bulations of intrinsic color, effective temperatures, and bolometric corrections as a function of spectral type, ıd the use of these intrinsic colors in studies of the interstellar reddening law; and (2) studies of special classes ' objects. Work in the first category was carried out mostly by Johnson working alone; work in the second ıtegory was done by a number of investigators, including in particular Mendoza and Johnson (both separately ıd together).

It is clear that one of Johnson's primary motivations for extending wideband photometry into the infrared as his desire to improve the effective temperature scale for stars cooler than the Sun. No doubt he was ıcouraged in this direction by G.P. Kuiper, the Director of the Lunar and Planetary Laboratory, who earlier ad worked on the problem of determining stellar effective temperatures (Kuiper 1938).

The procedure used essentially involves judging the *color* temperatures of stars by comparing their observed ıergy distributions, as indicated by the calibrated photometry, to Planckian flux curves; for stars cooler ıan the Sun a significant portion of the flux (and in extreme cases nearly all the flux) is radiated in the frared. Bolometric magnitudes, and hence the bolometric corrections to be applied to the visual magnitudes, ın be obtained from the same data by measuring the area under the flux curve. Then, for those few stars ith measured angular diameters, one can calculate the *effective* temperature from the angular diameter and ɔlometric magnitude. Having satisfied himself that his color temperatures were consistent with the effective mperatures for the angular-diameter standards, Johnson felt justified in using the term "effective temperature" henever discussing temperatures derived from the multicolor photometry.

Before the advent of infrared multicolor photometry, the only bolometric magnitudes available for cool stars ere the handful of radiometer measurements made at Mount Wilson three decades earlier (Pettit & Nicholson)28, 1933). Furthermore, the temperature scale in use in the early 1960s still relied on the effective temperatures ərived by Kuiper (1938) from those same radiometer measurements and the even earlier measurements of ıgular diameter obtained with the Mount Wilson interferometer.

The problem with the early unfiltered radiometer measurements (the "one-shot" approach to measuring ɔlometric magnitudes) is that the infrared is chopped up by strong atmospheric absorption bands, and a ɔrrection must be made for the substantial fraction of the flux that is blocked. But if one does not know ıe star's energy *distribution* throughout the infrared —and hence the relative weights of the different spectral gions— one cannot calculate this correction properly, no matter how well the atmospheric absorption spectrum known. With his multicolor data, Johnson found that bolometric fluxes had been underestimated in the earlier ork, so that an upward revision to the temperature scale was needed (Johnson 1966).

Johnson's effective temperature scale for cool stars, based on new photometry but the same angula diameters as Kuiper (1938) had used, was not improved upon for more than a decade. The scale currentl in use (Ridgway et al. 1980), which assigns still higher temperatures, was derived by combining infrared pho tometry with new angular diameters obtained from observations of lunar occultations.

Mendoza's early work in infrared photometry emphasized observations of special kinds of cool stars including carbon stars, Mira variables, "infrared stars," and T Tauri stars. This work led to a number o very interesting and sometimes unexpected results, as many of the objects he observed had not previously bee observed at infrared wavelengths. The study of carbon stars by Mendoza & Johnson (1965) provided credibl temperatures for a class of stars whose temperatures are notoriously difficult to estimate spectroscopically.

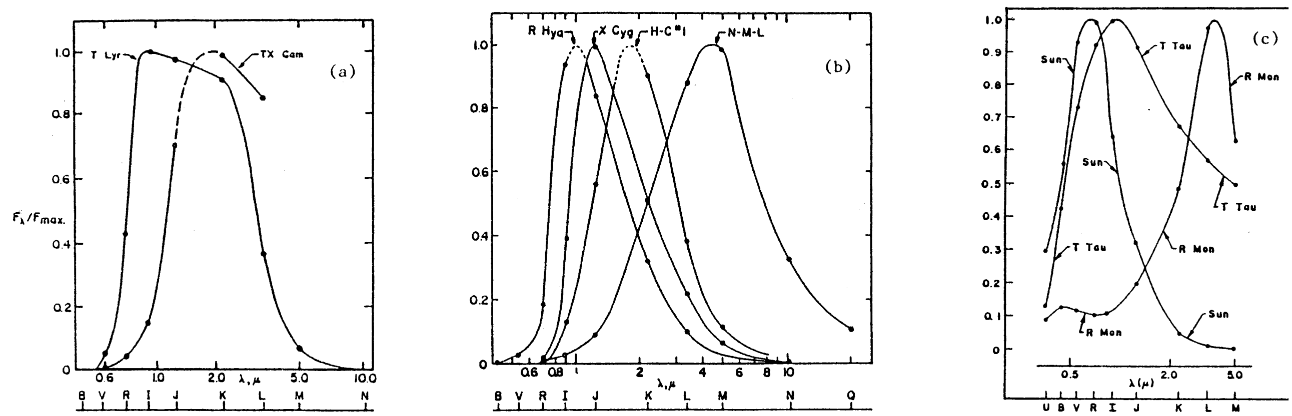

Fig. 1. Spectral energy curves for late-type stars. Photometry on the standard wideband system, calibrate and normalized to the flux maximum, is plotted against wavelength for (*a*) the carbon star T Lyr and the ver late M-type variable TX Cam (Mendoza 1965); (*b*) two well-known Mira variables and two "infrared stars (Johnson et al. 1965); and (*c*) the Sun, T Tau, and the nebulous variable R Mon (Mendoza 1966).

In Figure 1, the spectral energy distributions of several very cool objects are reproduced from three o Mendoza's papers. In panel (*a*), the carbon star T Lyr is compared to the extremely cool M-type Mira variabl TX Cam (Mendoza 1965). Mendoza found that the flat-topped energy distribution shown by T Lyr, due largel to absorption in the J filter, is a common characteristic of carbon stars, making it possible to recognize star of this class from the wideband data alone. In panel (*b*), Johnson, Mendoza, & Wiśniewski (1965) compar two well-known Miras, R Hya and χ Cyg, to two recently-discovered "infrared stars," as extremely red object found in infrared surveys were then called. The Two-Micron Sky Survey, carried out by a group from Caltec on Mount Wilson, was then nearing completion, and although its catalogue (Neugebauer & Leighton 1969) ha not yet appeared, several of the survey's most spectacular discoveries had been announced. The star "N-M-L in Fig. 1*b* is the object in Cygnus first reported by Neugebauer, Martz, & Leighton (1965) and later found to b a heavily-reddened M6 supergiant (Wing, Spinrad, & Kuhi 1967; Wing 1973), while "H-C #1" is one of severa very red stars in Cygnus found photographically by Haro and Chavira on near-infrared direct plates taken wit the Tonantzintla Schmidt (Johnson, Mendoza, & Wiśniewski 1965; see also Chavira 1967).

I would venture that the most exciting period of Mendoza's career must have come when he turned hi attention to pre-main-sequence objects and discovered their enormous infrared excesses (Mendoza 1966). I Figure 1*c* the energy distributions of T Tau and R Mon are compared to that of the Sun. Although it was wel known that T Tauri stars are usually found in dusty regions, I don't think anyone before 1966 anticipated tha so much of their observed radiation would be found in the infrared. In the case of R Mon, located at the tip o the cone-shaped nebula NGC 2261, most of the radiation is found in the K, L, and M filters.

Mendoza's (1966) announcement of the infrared excesses of T Tauri stars and related objects, in the forr of a five-page *Letter to the Editor*, was an observational paper with little attempt at interpretation. Indeed, i was not at all clear at the time whether these energy distributions represented emission or absorption spectra one star or several, or processes involving gas or dust. Yet surely this paper was one of the most influentia —'inspirational' might be a better word— papers of its period, as it opened up a major, and entirely new eld of study, namely the investigation of the early stages of star formation through observation of infrared nergy distributions. This development brought many young astronomers into the area of infrared photometry –including some— I'm sure, who would not have been attracted to it if infrared photometry were seen merely s a technique for measuring effective temperatures and bolometric magnitudes.

Since relative and absolute energy distributions can be plotted in any number of different ways, it may e worth commenting on the choice made by Mendoza (Fig. 1). By applying an absolute calibration to the ıagnitudes and normalizing each flux curve to its peak, he presented his data in a way that is particularly easy ɔ understand. The reader sees the information content of the photometry at a glance and easily ranks stars ccording to their color temperature. Also, by writing the filter names along the wavelength scale, he left no oubt as to which point represents which filter.

The chronology of the early days of infrared photometry surely must be considered remarkable. From the rst measurements in K and L reported in 1962, the field required only about five years to establish itself as fully-developed technique. By 1966 wideband photometry in the infrared was being done on a standardized nd calibrated system, and it had produced a review paper (Johnson 1966) as well as all the applications iscussed above, including a new scale of temperatures for stars cooler than the Sun. The development stage 'as essentially completed in 1967 with the introduction of the H filter and the detection of circumstellar dust.

2.3. Introduction and Use of the H Filter

In all the applications discussed so far, something is missing: the H filter at 1.65 μm, now a familiar ɔmponent of the standard system, was not used. Where did this filter come from, and why is it important?

The filters of the wideband infrared system were chosen to measure stellar temperatures and bolometric ıagnitudes, without regard to the positions of stellar spectral features. They were placed in atmospheric 'indows and were made as wide as the atmosphere would allow, in order to include as much of the star's ıdiation as possible. Perhaps Johnson did not feel that an additional data point at 1.65 μm was necessary ɔr determining temperatures, total energies, or interstellar reddening laws; or perhaps there was a technical ifficulty in obtaining such a filter. The lack of an H filter in the early days is certainly not the fault of the arth's atmosphere, since the window at H is the cleanest of any of the infrared bands (Ridgway 1974). In any vent Johnson's (1966) review article, which is still often used for its absolute calibration data and tables of ıtrinsic colors as a function of spectral type, does not include H.

In presenting the data shown in Figure 1, Mendoza called attention to the wide gap between the J and ʻ filters and the difficulty of drawing the flux curves of stars whose maxima occur within this gap: note that e used dashed lines for TX Cam and H-C #1 in this region. An additional data point would also aid in the ıterpretation of the flat-topped spectra of carbon stars.

Although I consider myself reasonably familiar with the literature on infrared photometry, I needed several ours in the library to track down the first use of the H filter. It was not routinely used until the end of the ecade —e.g., in California by Hyland et al. (1969) and in Arizona by Low et al. (1970). But its first use can e traced to Mendoza (1967) who gives a half-sentence description of the filter in a paper dealing primarily with 'BVRI photometry of long-period variables. [Dr. Mendoza confirms that this was the first use of H, and he dds that the filter was provided to him by Johnson]. Since Mendoza (1967) includes Julian Days in his data ıbles, we can pin down the first use of the H filter more precisely as the night of October 7–8, 1966.

I mention the introduction of the H filter not just to prepare the reader for the next game of Trivial 'ursuit©, but because it represents an important milestone in the development of the infrared standard system. ince H can be measured with the same photometer and detector as J and K, and to the same accuracy, JHK hotometry forms a well-defined unit. But more important, the H filter provides new information. A point t 1.65 μm may not be needed for determining effective temperatures and interstellar reddening curves, but it oes tell us something about the stars observed.

If the flux in H could be obtained satisfactorily by some kind of interpolation between J and K, the ıeasured flux would be redundant. But in fact this is not the case. In the JHK color-color diagram, *viz.* the lot of $J-H$ vs. $H-K$ (see Figure 2 below), the points for normal stars do *not* all fall along a single relation. 'he sequence for M dwarfs is quite different from the sequence for M giants and supergiants, and the relations ɔr K giants of differing metallicity are displaced from one another. Thus JHK photometry provides some ıformation about luminosity and/or metallicity that can not be obtained from just J and K. Since about 1970 he JHK color-color diagram has become one of the important tools of infrared photometry.

Theoretical flux distributions that were computed from model atmospheres to aid in the interpretation of he early infrared spectra obtained with the Stratoscope balloon (Woolf, Schwarzschild, & Rose 1964) showed distinct flux peak near 1.65 μm caused by the minimum in the absorption function of the negative ion of

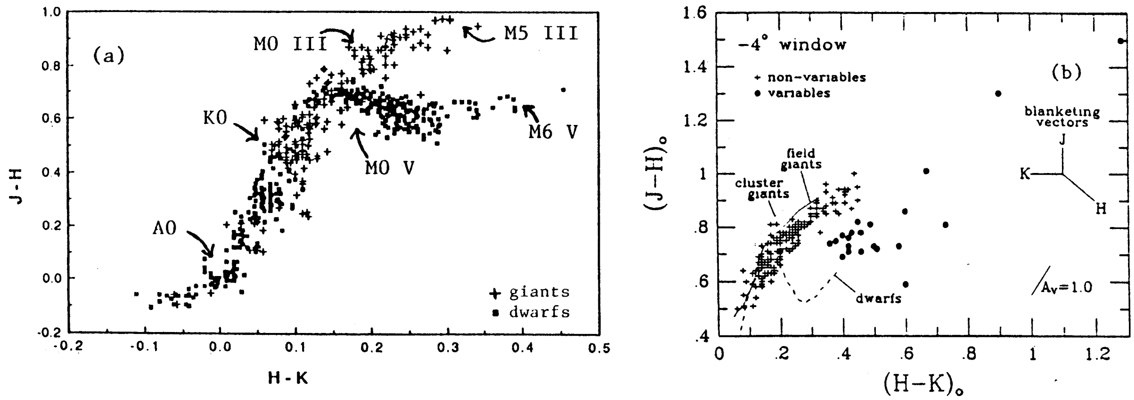

Fig. 2. JHK color-color diagrams. (a) Field giants and dwarfs, showing the bifurcation into two distinc sequences beyond spectral type M0 (adapted from Bessell & Brett 1988). (b) Stars of the galactic bulge showing their displacement to the right of the field giant relation (Frogel & Whitford 1987). Blanketing vector: and the slope of the reddening line are also indicated.

hydrogen, H^-, which dominates the infrared opacity of all G, K, and early M stars. Although the effects o H^- are much more clearly seen in narrow-band observations which have been designed for this purpose (Win{ 1991b), its effects on wideband data are also undeniable (e.g., Bell et al. 1976).

Perhaps the most remarkable feature of the JHK color-color diagram is the clear separation of M dwarfs from stars of higher luminosity, best seen in the data compiled by Bessell & Brett (1988) and shown in Figure 2a. This separation has not been explained quantitatively, but it is at least partially understood. One contributor to the luminosity effect is the smaller effect that H^- has on the energy distributions of dwarfs, due to the small temperature difference between the bottoms and tops of their convective photospheres. Another is the much greater strength of stellar H_2O bands, which depress H and K more than J, in M dwarfs as compared to M stars of higher luminosity (Wing 1991a).

Also impressive is the sensitivity of the JHK colors of K giants to metallicity. That is to say, when metal-deficient K giants belonging to globular clusters are plotted in the JHK color-color diagram, the points fall systematically to the left of the relation defined by stars of the solar neighborhood (Frogel et al. 1983). On the other hand, the stars of the galactic bulge have been found by Frogel & Whitford (1987) to fall to the right of the field giant relation (Figure 2b). This result constitutes a key piece of evidence that the stars of the galactic bulge are metal-rich, and it is mentioned here because it illustrates the far-reaching range of application of JHK photometry made possible by the inclusion of the H filter. At the same time, it should be mentioned that the metallicity effect on the JHK colors has never been satisfactorily explained in terms of the atomic lines, molecular bands, or continuous opacity sources that are strengthening or weakening in each filter as a function of metallicity to cause the observed effect. Until such an explanation is achieved, it seems advisable to be skeptical of metallicities derived on the basis of JHK photometry alone.

2.4. Interstellar Reddening Laws and Circumstellar Dust

It has been known since the 1930s that the plane of the Galaxy is pervaded by interstellar dust which absorbs light in a wavelength-dependent manner, so that distant stars appear redder as well as fainter. It has also long been appreciated that the magnitudes of distant stars must be corrected for interstellar absorption if we are to obtain an undistorted picture of the structure of the Galaxy. The reddening of any object is usually expressed as the color excess in a particular color index, say $E(B-V)$. This quantity is generally quite easy to obtain since it is simply the difference between the observed color index and the intrinsic value, which for most kinds of stars can be judged from the spectral type. It is much more difficult to determine the absorption at a given wavelength, e.g., the visual absorption A_V, and this is the quantity needed for photometric distance determinations. Various attempts to measure the absorption have long seemed to converge on the conclusion that A_V is about $3\times$ E$(B-V)$, but there have also been indications that the ratio $R = A_V/E(B-V)$ may sometimes be significantly greater than 3 (Turner 1994).

During the 1950s, while Harold Johnson was primarily occupied with UBV photometry of open clusters and the determination of cluster distances, he was very much concerned with the effects of interstellar reddening on his photometry but was often forced to assume the nominal value $R = 3.0$ to obtain the absorption. Multicolor infrared photometry, on the other hand, provides a simple and direct way of determining R for the dust in any line of sight. If this was not Johnson's initial motivation for extending his photometric system into the infrared, at least we can state that the determination of interstellar reddening laws soon became an application which consumed much of his attention and energy.

Let us review the procedure by which interstellar reddening "laws" —the variation of interstellar absorption with wavelength— and the value of R are obtained from multicolor photometry. We need to understand the procedure to see how this work ultimately led to the detection of circumstellar dust shells around many stars and how these dust shells, before they were recognized as such, wreaked havoc upon attempts to determine interstellar reddening laws.

Johnson called the procedure the "color-difference method". It is based on (1) the observation, on the multicolor system, of heavily-reddened stars of known spectral type, and (2) knowledge of the intrinsic colors of stars of the same spectral types. The necessary intrinsic colors are given in Johnson (1966); they were used in his study of "Interstellar Extinction in the Galaxy" (Johnson 1965) and in a review paper on "Interstellar Extinction" that appeared later (Johnson 1968). A significant problem with this method, unfortunately, is that stars which are far enough away to be reddened enough to be useful —and yet bright enough to be observable in the infrared and to have known spectral types— are almost invariably supergiants; and supergiants are among the hardest stars to compile intrinsic colors for, since even the nearest examples are likely to be reddened. For the M supergiants, Johnson's response to this problem was to assume that supergiants have the same intrinsic colors as normal giants of the same spectral type. This assumption turns out to be wrong, and its frequent use has caused a good deal of confusion over the years. One reason that the assumption is wrong is that, in the region of the *UBVRI* filters, the colors of M stars are strongly affected by TiO absorption bands; but the formation of TiO molecules depends upon gas pressure as well as temperature, so that giants and supergiants of the same spectral type (TiO strength) must have different temperatures and hence different colors. Another reason, as we shall see, is that M giants rarely have circumstellar dust shells, whereas M supergiants nearly always do.

In any event, given the observations of reddened stars and a table of intrinsic colors, we may proceed as follows to construct interstellar reddening laws like the ones shown in Figure 3, which are from Johnson (1968). For each star observed, color indices are formed relative to the V filter —*viz.* $U - V, B - V, V - R, V - I$, etc.— always with the filter of longer wavelength on the right so that an algebraically larger index corresponds to a redder color. Color excesses $E(U - V)$, etc. are then found by subtracting the assumed intrinsic colors from the observed ones. Next, the color excesses are normalized by dividing the set by the value of $E(B - V)$; this normalization allows the color excesses of different stars to be directly compared or averaged together, even if the stars are seen behind different amounts of dust. Then to obtain the curves of Fig. 3, one simply plots the normalized color excess ratios $E(V - X)/E(B - V)$, for any filter X, against the effective wavelength of that filter. Note that wavelengths are plotted "upside-down and backwards," as Albert Whitford is fond of saying. This choice renders the curve roughly linear over most of the range shown, and more important, it makes easy the extrapolation to infinite wavelength, which is then just a short step beyond the last data point.

To determine R, the ratio of total absorption to selective absorption $A_V/E(B - V)$, from the interstellar reddening law, we need only decide on the value of the ordinate where $1/\lambda$ equals zero. The assumption here, rooted in the theory of light scattering by small particles, is that the absorption decreases steadily with increasing wavelength and asymptotically approaches zero at infinite wavelength. In Fig. 3*a*, I have drawn a horizontal line representing this asymptote and arrows representing the absorption at wavelengths corresponding to the V and I filters. Since these are the absorptions corresponding to an amount of dust that produces a color excess of $E(B - V) = 1.0$, and since the curve passes through zero at the position of the V filter, the height of the horizontal line in magnitudes directly gives the value of R.

For the region in Perseus (Fig. 3*a*), Johnson obtained the normal result $R = 3.0$. It is based on observations of 21 stars of widely varying spectral types; the data do not go beyond the L filter at 3.5 μm, but the extrapolation to infinite wavelength seems well determined. For Cepheus (Fig. 3*b*), on the other hand, the result is altogether different: the curve shows a pronounced upturn at the longest wavelengths, leading to the value $R = 4.8$. How can we interpret this result? If we suppose, as Johnson did, that all color differences between the reddened star and the tabulated intrinsic values are caused by the interstellar medium, then the Cepheus curve implies that the absorption in this direction, for a given observed color excess $E(B - V)$, is much greater than would normally be supposed, and that reddened stars in this direction are not as far away as we thought. Johnson proposed that the absorption toward Cepheus is the sum of two components: a normal component having a Perseus-like wavelength dependence and a normal ratio $R = 3$, and a neutral component, perhaps due to larger grains, which affects all wavelengths equally.

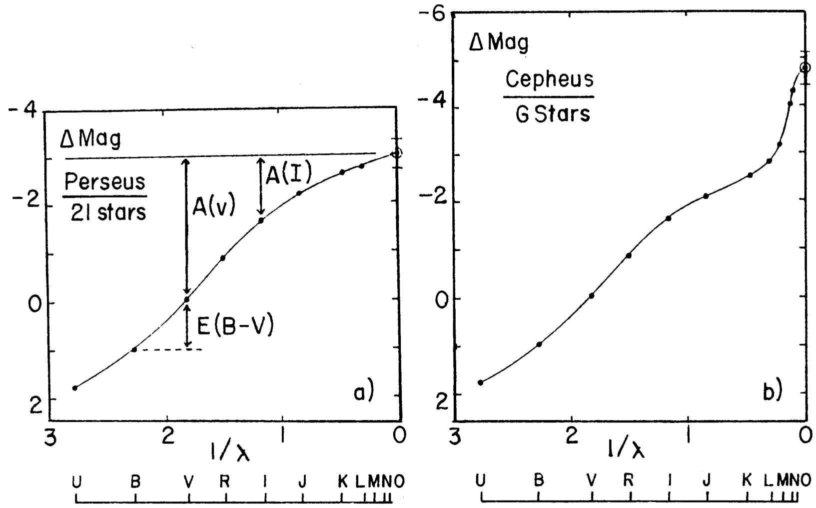

Fig. 3. Interstellar reddening laws for Perseus and Cepheus, after Johnson (1968). The asymptote approache by the Perseus curve, and arrows defining A_V, A_I, and $E(B-V)$, have been added. The long-wavelengt data for Cepheus depends almost entirely upon a single star, μ Cep, an M2 Ia supergiant with a substantia circumstellar dust shell.

Among the reddening laws plotted by Johnson (1965, 1968) are quite a few showing far-infrared upturn leading to large values of R. The implication was that neutral absorption occurs in many regions of the Galax and that our picture of galactic structure was greatly in need of revision. In particular Johnson (1968) suggeste that, since distances had previously been systematically overestimated, a reduction of 25–30 % in the distanc to the galactic center was in order. And to the extent that the extragalactic distance scale is tied to distanc determinations within the Galaxy, it would be only a small additional step to suggest that the discovery c neutral extinction had profound cosmological implications.

If we examine the data upon which the reddening laws are based, we find that relatively few stars wer observed at wavelengths longer than L (3.5 μm), and that these were mostly late-type supergiants. Mor particularly, most of the curves showing pronounced upturns represent cases in which only a single very luminou supergiant was observed at the longest wavelengths. In the case of the Cepheus region, 6 stars were observe out to K and 5 out to L, but the long-wavelength upturn is based on only two stars —μ Cep (M2 Ia) and to lesser extent HR 8752 (G0 Ia), two of the most luminous stars known in the Galaxy.

Today we recognize that late-type supergiants undergo extensive mass loss and are commonly surrounde by substantial circumstellar shells containing dust grains which are heated by the absorption of starlight an which re-radiate this energy in the infrared. The resulting infrared excesses tend to be greatest in the mos luminous stars, and the upturn in Fig. 3*b* simply reflects the infrared excess of μ Cep relative to the colors of normal M2 III giant.

The infrared excess of μ Cep was demonstrated conclusively a short time later by Woolf & Ney (1969 Earlier spectrophotometry by Gillett, Low, & Stein (1968) had left it unclear whether the spectrum should b interpreted as showing absorption from 7.5 to 9.5 μm or emission from 9.5 to 14 μm, but the new calibration c the spectrum by Woolf & Ney left no doubt that strong emission, reaching 5 times the height of the continuun was present. They also showed that the spectrum of the excess emission was much more steeply peaked than blackbody and in fact agreed reasonably well with computed emissivity functions for silicates such as olivin This work clearly established both the infrared excesses of M supergiants and the circumstellar origin of th emission; the authors did not, however, comment on the implications of their results to published studies c interstellar extinction.

Before the circumstellar emission of μ Cep and other stars was established, Johnson himself expresse doubts about the interpretation of his interstellar extinction curves. He pointed out (Johnson 1967b) that th infrared photometry of Of and Be stars like ϕ Per, from which he had derived an interstellar extinction cur with a huge far-infrared upturn, might better be explained in terms of infrared emission from circumstell shells. He also reexamined the question of the intrinsic colors of M supergiants (Johnson 1967a), realizing th it is not impossible that these reddened stars have large infrared excesses, compared with the unreddened stars sed as standards," and he concluded that "It is possible to explain *part* (emphasis mine) of the large infrared xcesses of reddened M supergiant stars as intrinsic stellar radiation." In connection with the star NML Cyg he ostulated a "relatively distant, circumstellar, dust cloud, which absorbs a fraction of the shorter-wavelength utput of the star and re-radiates it at very long wavelengths."

The above quotations are, I believe, as far as Johnson ever went toward retracting his published claims f discovering a neutral component of the interstellar extinction. Unfortunately, neither he nor anyone else, o my knowledge, said clearly and in print that his conclusions regarding neutral extinction and large values f R should simply be disregarded. Adding to the confusion was the fact that Johnson's two major papers n interstellar extinction (Johnson 1965, 1968) were, despite the 3-year difference in publication date, actually ritten at the same time and present largely the same data and conclusions. By the time the volume containing is review paper finally appeared in 1968, its contents were seriously out of date. Shortly after it appeared I ad an opportunity to meet with Dr. Johnson in his office in Tucson, and I could not resist asking him why he ad not withdrawn the paper or at least attempted to revise it, if he knew that its conclusions were wrong. His eply was, I believe, typical of him: he was, he said, no longer interested in interstellar extinction curves, and e would much rather talk to me about his new Fourier-transform spectrometer!

3. CHARACTERISTICS OF THE CIRCUMSTELLAR DUST EMISSION

Now we must "fast-forward" to a time much closer to the present so that I can mention some of the things e have learned about the circumstellar dust shells of late-type stars. Because of limitations of time and space, will be able to give here only a cursory summary of results in a field which remains a very active one.

Circumstellar shells, and their effect on infrared energy distributions, can be divided into two broad ategories according to their "thickness". Very thick shells, which in some cases may shroud a star to the xtent that it is barely detectable in the optical region, produce emission characterized by blackbody energy istributions for the temperature of the grains. Photons emitted in these shells are likely to be absorbed and e-emitted many times before escaping, and no spectral signature is preserved. In these cases we can learn the emperature(s) of the shell(s), but not the grain chemistry. On the other hand if the shell is optically thin, or t any rate not extremely thick, we may expect to see a spectral signature indicative of the grain type. The pectrum of the excess emission then reflects the wavelength dependence of the grain emissivity, and a rather harp "bump" appears in the spectrum.

It was proposed more than half a century ago by Loreta (1934) and O'Keefe (1939) that the deep minima of R Coronae Borealis are caused by the ejection of matter and the sudden formation of graphite particles. In the arly days of infrared photometry, however, it was still thought that circumstellar dust particles occur relatively arely, i.e., only in the envelopes of very special kinds of stars. This view changed abruptly as ground-based pectrophotometry in the 8–14 μm window, starting with the work of Gillett et al. (1968) mentioned earlier, howed dust bumps peaking near 10 μm in star after star. The spectrophotometry of Merrill & Stein (1976) howed that the grains around oxygen-rich and carbon-rich stars are clearly different, their bumps peaking at lifferent wavelengths. And with the spectrophotometry as a guide to interpreting the wideband photometry hat existed on the standard system for a much larger number of stars, it became clear that virtually all stars hat are sufficiently cool and/or luminous have enough solid material in their circumstellar envelopes to affect heir 10 μm photometry. Never again would N magnitudes be trusted in the determination of interstellar eddening laws. In fact, N magnitudes went out of fashion completely since the 8–14 μm window is wide nough to contain several intermediate-bandwidth filters, by which one can separate the dust bump from the ontinuum and determine both the amount of dust and the grain type.

Most of the observational data on circumstellar shells that we have today were obtained by the *IRAS* atellite, which operated for 10 months in 1983. The four-color photometry at 12, 25, 60, and 100 μm rovides information especially about the thickest and coolest shells, while data taken with the Low Resolution Spectrometer (LRS) in the 8–22 μm interval show the shape of the dust bumps. The LRS spectra have, in fact, llowed literally thousands of circumstellar shells of late-type stars to be classified according to the strength of he emission in the bump (i.e., the amount of dust) and its peak wavelength (i.e., the grain type); the statistical haracteristics of stars showing the silicate feature have been examined by Noguchi (1990) and others. Little-Marenin (1986) has compared the shapes of the dust bumps of different stars after subtracting a blackbody photospheric contribution from the LRS spectra (Figure 4). She finds that very nearly all dust bumps have ne of two distinct shapes: the silicate feature, seen in the spectra of oxygen-rich stars, which peaks at 9.7 μm; nd the SiC feature, seen in most carbon-rich stars, which peaks at 11.2 μm. Models of the dust based on hese spectra have been presented by Bode (1988) and others. Curiously, Little-Marenin (1986) and Willems &

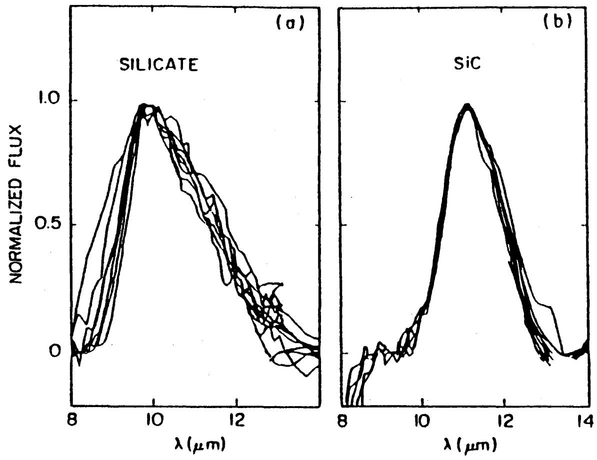

Fig. 4. Comparison of "dust bumps" of (a) oxygen-rich, and (b) carbon-rich stars after subtraction of tl underlying stellar continuum and normalization to the peak (after Little-Marenin 1986 and Bode 1988).

de Jong (1986) found several carbon stars with silicate dust shells; further examples of this phenomenon ha subsequently been found in the LRS database (Chan & Kwok 1991; Kwok & Chan 1993) bringing the number known cases to about 15. Studies of the optical spectra of these carbon stars (e.g., Lloyd Evans 1990) have show that most of them are examples of the so-called J-stars, with enhanced ^{13}C. What the connection is betwee isotopic carbon abundance and having the "wrong" type of circumstellar grain is by no means clear. Nor h it been decided whether these objects should be interpreted as single stars which have only recently becon carbon stars (Willems & de Jong 1988; Chan & Kwok 1988), or whether the binary (M+C) model favored l Little-Marenin (1986), or some variation thereof (Lloyd Evans (1990), is required. A related curiosity is the fa that RV Tauri variables seem to have silicate grains in their circumstellar envelopes no matter whether the photospheres are oxygen-rich or carbon-rich (Lloyd Evans 1985).

Finally, we might inquire as to the grain type of the S stars, whose photospheres are intermediate to the and C stars as regards the O/C ratio. Do they have an intermediate type of grain? According to Little-Maren & Little (1988), most S stars show *either* silicate features *or* SiC features; some show neither, and some sho both, in various proportions. In the latter case, it would be interesting to know whether both types of grai exist in the same shell, or if they represent mass loss from different epochs. Clearly there is still much to l learned about the grains surrounding late-type stars.

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DISCUSSION

Dufour: Have the strengths of the Si and C IR "bumps" been correlated with the mass loss rates of the stars'

Wing: Yes, the strength of emission in the bumps has been compared to various mass loss indicators, includin in particular the microwave CO emission as well as indicators from optical spectroscopy. The general conclusion are that the dust bump seem to be good indicator of the mass loss rates, and that dust seems to form whereve mass is lost (with gas/dust ratios of about 100). Frankly, I don't understand why the correlation is so good since the IR emission should relate more closely to the total amount of dust (i.e., the time integral of the dus mass loss rate) than to the rate of mass loss and there are indications that not all cool stars have had the sam mass loss history.

R.F. Wing: Astronomy Department, Ohio State University, 174 W. 18th Ave., Columbus, OH 43210 U.S.A
e-mail: ts4718@ohstmvsa.bitnet.