# Stellar Spectra in the *H* Band

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*[Ed. note: Since this paper was given, the AAVSO has placed 5 near-IR SSP-4 photometers with observers around the world;* J *and* H *observations of program stars are being obtained and added to the AAVSO International Database.]*

**Abstract** The *H* band is a region of the infrared centered at wavelength 1.65 microns in a clear window between atmospheric absorption bands. Cool stars such as Mira variables are brightest in this band, and the amplitudes of the light curves of Miras are typically 5 times smaller in *H* than in *V*. Since the AAVSO is currently exploring the possibility of distributing *H*-band photometers to interested members, it is of interest to examine the stellar spectra that these photometers would measure. In most red giant stars, the strongest spectral features in the *H* band are a set of absorption bands due to the CO molecule. Theoretical spectra calculated from model atmospheres are used to illustrate the pronounced flux peak in *H* which persists over a wide range of temperature. The models also show that the light in the *H* band emerges from deeper layers of the star's atmosphere than the light in any other band.

## 1. Introduction

When multicolor photometry in the infrared was first standardized in the 1960s, Harold Johnson and his colleagues acquired filters to match the windows in the atmospheric absorption and named them with letters of the alphabet (Johnson 1966). It was only by fortunate coincidence that the widths of the windows between the main bands of atmospheric water vapor are about right for the filters of a wideband multicolor system. The photometric bands (windows) were named alphabetically in order of wavelength following the letter *I* (which was already understood to mean the nearest infrared, just beyond the red). The infrared filters, in combination with the established optical ones, then formed the *UBVRIJKLMN*…system (Table 1). In this early work, for several years, there was no *H*.

Historical research (Wing 1994) has shown that it was Eugenio Mendoza of Mexico who introduced the *H* band, using a filter provided by Johnson in 1966 (Mendoza 1967). This was an important addition for several reasons. Of all the infrared windows, the *H* band, located halfway between the *J* and *K* bands, is the cleanest. It plugs a significant gap in the energy distributions of stars obtained by multicolor photometry, and it is right at the highest point of the energy distributions

Table 1. Central wavelengths of filters of the standard wideband photometric system.

| *Filter* | *Wavelength (μm)* | *Filter* | *Wavelength (μm)* |
|---|---|---|---|
| *U* | 0.36 | *H* | 1.65 |
| *B* | 0.44 | *K* | 2.2 |
| *V* | 0.55 | *L* | 3.4 |
| *R* | 0.70 | *M* | 5.0 |
| *I* | 0.90 | *N* | 10: |
| *J* | 1.25 | | |

of many cool stars. According to Dr. Mendoza (1993), it was only by historical accident that this important band was skipped in the early work and later named out of alphabetical order: Johnson had simply been unable to acquire a suitable filter for the *H* band, and he went ahead without it.

As readers may be aware, the Council of the AAVSO have been discussing the possibility of adding some kind of infrared photometry to the organization's observing repertoire, and a Working Group on Infrared Photometry has been established. Since multicolor infrared work does not seem feasible for private, low-budget observatories, considerable thought has been given to the question of which single infrared filter would provide the most useful supplement to the visual light curves which will undoubtedly remain the major part of the organization's database. The *H* band has been selected, and it is the purpose of this paper to discuss the reasons for this choice.

In the infrared, the longer the wavelength the brighter the background. Indeed, at the longer infrared wavelengths (beyond about 3 μm), one has to observe through the thermal emission from not only the atmosphere but also the telescope mirror and anything else in the optical path. With increasing wavelength, the technology needed for cooling, chopping, etc. becomes rapidly more elaborate and expensive. The *H* band, at 1.65 μm, represents the longest wavelength (and hence the most different from *V*) which we think can be measured in a reasonable number of stars with a small telescope and a simple (thermoelectric) system to cool the detector. In addition, the excellent transparency of the earth's atmosphere in the *H* band should allow good photometry to be obtained from sea-level observatories.

Most of this paper will deal with spectroscopic information, of two kinds: (a) the position of the *H* band within the spectral energy distributions of stars of different types, and (b) the spectral content of the *H* band, i.e., the molecular bands and atomic lines that fall within this window and absorb some of the radiation. Theoretical spectra will be used for this purpose. In Section 5 we will briefly consider the character of the light curves that cool variables are expected to show in *H*, and what we can learn from them.

## 2. Synthetic spectra

A spectrum calculated from a mathematical model of a stellar atmosphere is commonly called a "synthetic spectrum," and the magnitudes and colors obtained by multiplying a synthetic spectrum by a set of filter response functions are called "synthetic photometry" and "synthetic colors." The calculations are horrendous, but once the programs and line lists are set up, even a theoretician can enjoy doing photometry!

An important application of synthetic photometry is to derive fundamental parameters of stars such as effective temperature and gravity. This is done by comparing synthetic colors to observed colors. When a good match is obtained for a sufficiently extensive set of colors, the effective temperature of the model used to generate the synthetic colors is taken to be the effective temperature of the matching star. This type of comparison, which usually involves a collaboration between (at least) two people, makes both the observations and the calculations much more useful than they would be by themselves. To turn the observed colors and indices into fundamental stellar parameters, the model atmospheres are indispensable. At the same time, the models would be of limited value if they were not tested through comparison of observed and synthetic spectra and colors. The authors of this paper were involved in just such comparisons when we realized that the figures we were generating might be of interest to the AAVSO, especially to members involved in the development and use of an *H*-band photometer.

A model atmosphere specifies the temperature, gas pressure, etc. of each atmospheric layer, and this in turn determines the degree of ionization and excitation of each type of atom, as well as the equilibrium between atoms and molecules, in each layer. The photons making up a star's spectrum arise from a range of depths in the atmosphere, and their probability of escaping from the star depends upon the absorption characteristics of these atoms and molecules. A tremendous amount of atomic and molecular data must therefore be stored in the computer before a realistic spectrum, with all its absorption lines, can be computed. The difficulties are especially severe for the coolest stars, since the molecules that form at low temperatures have very complex absorption spectra.

The development of programs to compute model atmospheres, and the compilation of the necessary line lists for all the relevant atoms and molecules, has been the work of a great many people over several decades (see, for example, Gustafsson and Jørgensen 1985, 1994). Until quite recently, however, applications of synthetic spectra were mostly limited to stars warmer than about 4000 K. For cooler stars, comparisons with observation were discouraging—the models were known to be deficient, the line lists were incomplete, and some important molecules could not yet be included in the calculations at all. In the last few years, however, the situation has changed dramatically, primarily as a result of the inclusion of water vapor, which grossly affects not only the spectra of cool stars but also the structure of their atmospheres (Jørgensen *et al.* 2001). Current models for cool stars are computed with opacities based on 50 million or more lines from the water molecule alone!

Once synthetic spectra can be calculated correctly, they constitute an excellent educational tool. One can, like a spectroscopist, explore a limited region of the spectrum in detail, or one can compute the entire spectrum, from zero wavelength to infinity, and examine the overall energy distribution. We will do a little of both.

**3. Energy distributions of dwarfs and giants**

The synthetic spectra of a set of solar-composition dwarfs (i.e., main-sequence stars) of various temperatures are shown in Figure 1. They were computed at the Niels Bohr Institute in Copenhagen, using model atmospheres calculated with the MARCS code, which was originally developed at the Uppsala Observatory in Sweden.

The quantity plotted is the flux per unit frequency interval. It may seem odd to plot the flux in frequency units against the wavelength, but this choice gives the best (flattest) presentation of the spectra in the region of interest. To interpret the overall energy distributions, it is helpful to compare them to blackbody curves plotted in the same units (Figure 2). These blackbody curves represent the energy distributions

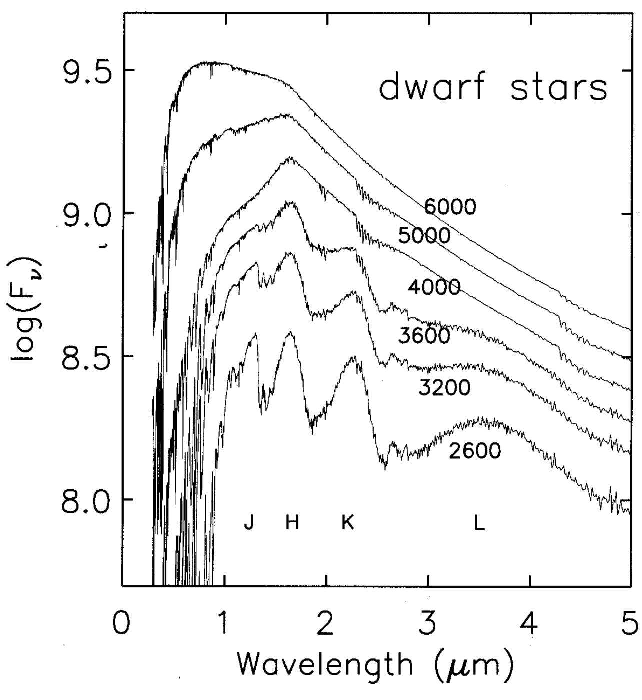


Figure 1. Synthetic spectra of 6 main-sequence stars, ranging in effective temperature from 6000 K to 2600 K. The logarithm of the flux per unit frequency interval is plotted against the wavelength in microns. The wavy shape of the coolest three spectra is caused by absorption by stellar water vapor. Peaks in the spectra of the cooler stars correspond to regions of reduced water absorption, which define the photometric bands *J*, *H*, *K*, and *L*. Other features are discussed in the text.

of perfectly-emitting surfaces of unique temperatures, without any spectral lines. The energy distributions of stars differ from blackbody curves for several reasons, mostly having to do with absorption processes. Atoms absorb in spectral lines (only a few of which can be seen at the low resolution of Figure 1), while molecules produce broad absorption bands (which are collections of lines). In addition, there are sources of atmospheric opacity that produce continuous but wavelength-dependent absorption, causing distortions in the shape of the spectrum.

Note that the wavelength scale of Figure 1 extends from zero to 5 microns (μm). Nearly all of this is in the infrared, which starts at about 0.75 μm. The visual region of the spectrum, from 0.40 to 0.75 μm, is not well shown in this type of plot.

The stars of Figure 1 represent a temperature sequence. At the top is a main-sequence star of 6000 K, similar to the Sun. At all wavelengths beyond about 0.5 μm the spectrum is fairly smooth, approximating the shape of a 6000 K blackbody. The main departure from the blackbody shape is an excess of radiation, or "hump," at approximately 1.65 μm—which, you will note, is the position of the *H* band. This hump becomes more pronounced at 5000 and 4000 K, and the spectra take on a remarkable triangular shape. This feature is caused by the wavelength dependence of absorption by the negative hydrogen ion ($H^-$, being a proton with two electrons). Photons in the part of the spectrum shortward of 1.65 μm have enough energy to knock one of the electrons from an $H^-$ ion, being absorbed in the process (bound-

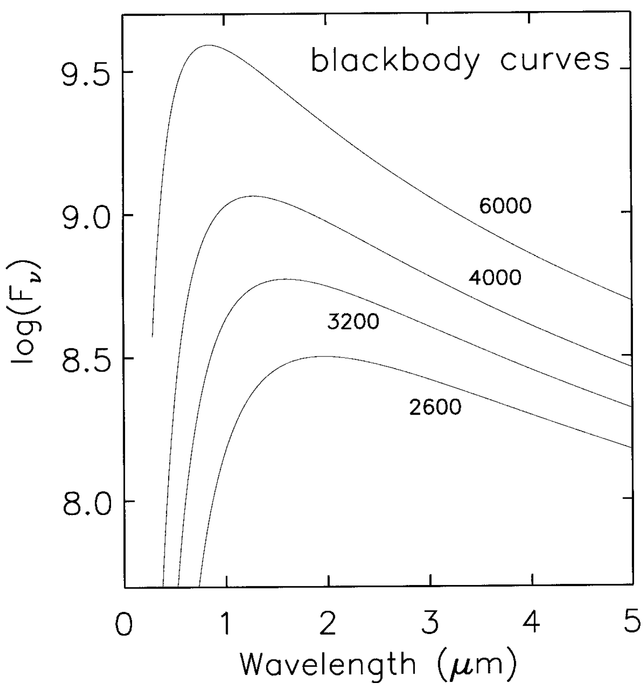


Figure 2. Blackbody curves for temperatures 6000, 4000, 3200, and 2600 K, plotted in the same units as the synthetic stellar spectra of Figures 1 and 3.

free absorption), while photons at longer wavelengths can be absorbed by a free-free process (here a passing electron happens to be close to a neutral hydrogen atom when the photon comes by). The total absorption by $H^-$ is the sum of these two processes, which has a minimum value at 1.65 µm. This "$H^-$ opacity minimum" has been a well-known feature of the models for a long time, but it has been hard to study observationally because observers usually see only a small part of the spectrum at a time, mostly using uncalibrated observations taken through the earth's atmosphere. Mendoza was aware of this feature due to $H^-$ when making the first measurements with a 1.65 µm filter, and indeed this may have led to the choice of the letter H for this filter. If one is using multicolor photometry to study energy distributions, one would certainly want to include the *H* band, as it is the brightest point in the spectra of stars of a wide range of temperature.

Proceeding now to lower temperatures, the stars of 3600, 3200, and 2600 K in Figure 1 all have a different, wavy, appearance. These waves are caused by the absorption by water vapor, which is clearly present at 3600 K but is strongest in the coolest stars. This is line absorption, but there are so many lines—literally millions—that it behaves like a continuous opacity source. The letters *J*, *H*, *K*, *L* appear at the central wavelengths of these photometric bands, which are defined by the windows in the $H_2O$ absorption of the earth's atmosphere but which also correspond to regions of relatively low (but still significant) $H_2O$ opacity in stellar atmospheres. It is important to note that at stellar temperatures, there are no real "windows" in the absorption spectrum of water, only regions of reduced opacity. Fortunately, the cold (about 300 K) water vapor of the terrestrial atmosphere is unable to absorb effectively in the regions between the main bands, leaving the windows fairly clean. If the water of the earth's atmosphere absorbed in the same manner as the hot (3000 K) steam of stars, infrared astronomy from the ground would be out of the question.

We have seen that the *H* band occurs not only at the $H^-$ opacity minimum, but also at one of the minima of water opacity. Consequently, in all normal stars from approximately the temperature of the Sun to that of a cool Mira variable, the *H* band is the brightest point in the entire spectrum. We can also conclude that, as a result of the low opacity (high transparency) of stellar atmospheres in this region, the photons that we see in *H* are coming preferentially from deeper atmospheric layers than photons at other wavelengths. Whereas most optical/infrared observations of cool stars refer to their cool upper photospheres, observations in *H* allow us to study the warmer, lower parts of the photosphere.

A few other features of the spectra of Figure 1 are worth mentioning. At wavelengths below about 1 µm, the spectra fall off steeply and become very messy, especially at temperatures below 4000 K. This is the optical region, dominated by molecular bands (primarily metallic oxides, such as TiO and VO) as well as by atomic lines. The next time you estimate the magnitude of a cool star, remember that the light you see, of wavelength around 0.5 µm, represents only the faint tail of the star's broad energy distribution. The synthetic spectra shown here have been plotted on a tiny scale in order to include the whole region in which these stars are bright. The calculations, however, were carried out at much higher resolution and could be plotted on scales that show the individual lines.

Finally, the small wiggles in the 5000 K and 4000 K dwarfs near 2.5 μm and 4.5 μm are the first-overtone and fundamental bands, respectively, of carbon monoxide (CO). At lower temperatures they are still present but become lost in the stronger $H_2O$ absorption.

In Figure 3 we show the spectra of 5 giant stars. Again the illustration is restricted to stars of solar composition, although other cases have also been computed. These spectra are similar to the dwarf spectra in many respects, so we'll just point out the differences. The $H^-$ opacity minimum at 1.65 μm is clearly seen at 5500 K but becomes lost at cooler temperature because of numerous lines of atoms and molecules, which are much stronger here than in the dwarfs. The water bands are extremely strong at 2500 K, but they don't appear in giants until lower temperatures than in dwarfs—note that a 3000 K giant has only about the same amount of water absorption as a 3600 K dwarf. The CO bands near 2.5 and 4.5 μm are much stronger in the giants. In addition, bands of a number of other molecules, such as CN at 1.1μm and SiO starting at 4.0 μm, can be seen in the giant spectra.

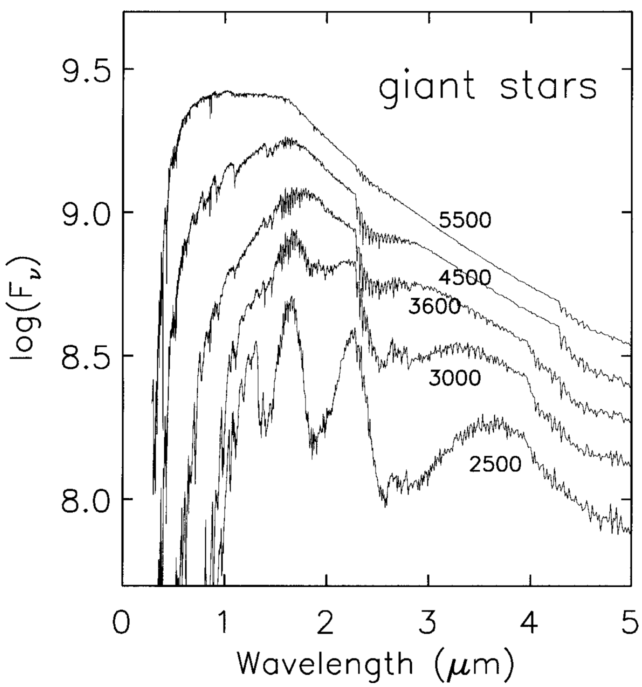


Figure 3. Synthetic spectra of 5 giants stars of solar composition. Most spectral features are stronger than in dwarf stars (Figure 1) because of the greater transparency of giant atmospheres.

In Figure 4, a 3000 K dwarf is shown together with its continuum. The continuum, you will recall, is the level of brightness that the star would have if there were no line absorption by atoms or molecules. In this case, the full spectrum (computed with all atoms and molecules included) does not approach the continuum anywhere in the infrared, and is typically about 0.2 dex (0.5 magnitude) below it. Observers never see the continuum of cool stars, but the models tell us where it is. This is useful to know if we are trying to measure the strength of an absorption feature: if we have only the observed spectrum, we are likely to grossly underestimate the amount of absorption. In a 3000 K dwarf (such as Proxima Centauri), the absorption shortward of 1.0 μm is mostly due to TiO, while nearly all the infrared absorption is due to $H_2O$.

The shape of the continuum is interesting in itself. We saw earlier that the spectrum of a 4000 K dwarf (Figure 1) has a triangular shape peaking at 1.65 μm because of the wavelength dependence of $H^-$ opacity. Now we see that this shape persists in the continuum to lower temperatures, and for the same reason. According to the models, the negative hydrogen ion remains the dominant source of continuous opacity at low temperatures, although its effects are hard to see once the water absorption appears.

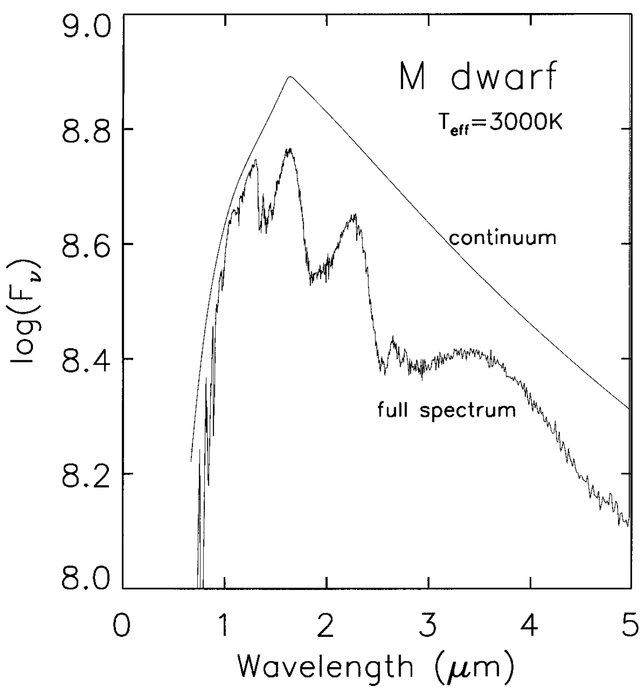


Figure 4. The synthetic spectrum of a 3000 *K* dwarf star, together with its continuum. The shape of the continuum is greatly distorted from a blackbody curve by the opacity due to $H^-$. The downward displacement of the spectrum from the continuum is almost entirely due to water absorption.

## 4. Spectra of higher resolution

Theoretical spectra have a number of nice properties which, to an observer, seem almost miraculous. The physical parameters of the model can be adjusted one at a time to study their effects on the spectrum. The chemical composition can likewise be varied. The spectra can be plotted at any resolution, to show any amount of detail, and the line list for any segment can be printed to identify the cause of every wiggle. But perhaps most remarkable is the possibility of turning "on" or "off" the absorption lines of any molecule, at will. In Jørgensen (2003) we describe all the atomic and molecular sources that we include in the model atmosphere and spectrum computations. Here we will show just one example of this capability.

In Figure 5, a shorter spectral interval from 1.2 to 2.4 µm (including just the *J*, *H*, and *K* bands) is shown for a 3000 K giant star. The continuum once again shows the hump at 1.65 µm due to the $H^-$ opacity minimum. The other lines in the plot show spectra computed for just one molecule at a time. These spectra are all based on the same atmospheric model; only the line lists are varied when calculating the synthetic spectra. The dotted line shows the spectrum of water, with everything else turned off. The solid-line spectrum includes bands of TiO (near 1.2 µm) and CO (near 1.6

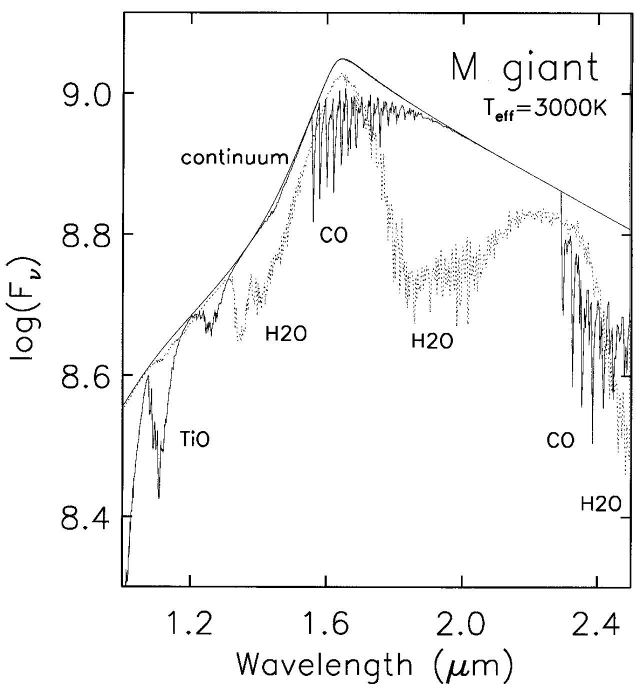


Figure 5. Components of the spectrum of a 3000 K giant in the region of the *J*, *H*, and *K* filters. The continuum, and spectra computed with $H_2O$ absorption only (dotted line), and with TiO and CO only (solid line), are plotted separately.

and 2.4 μm), with water and everything else turned off. The full spectrum, including the effects of all these (and other) molecules, is not shown but would be close to the lower envelope of the plotted curves.

At the higher resolution of Figure 5 (spectroscopic observers would call this "medium resolution"), we can now identify the main absorbers in the *H* band, which extends from 1.5 to 1.8 μm. The dominant feature is a set of second-overtone bands of CO which run entirely across the *H* band (and which appear only as "noise" in the low-resolution spectra of Figure 3). These CO bands are sufficiently strong to knock down the 1.65 μm hump, making it much less obvious. Plots of still higher resolution show many additional lines in the *H* band that are strong enough to be observed, mostly due to atoms and the OH molecule. The overall opacity in the *H* band, however, is lower than in any other band.

## 5. Photometry in the *H*-band

Some time ago, at a meeting in Toronto co-sponsored by the AAVSO, one of us described the light curves of Mira variables in the infrared (Wing 1986). We pointed out that cool Miras are very bright in the infrared, compared to their visual magnitudes, and that many of them would be bright enough to observe with small telescopes if only a suitable infrared photometer could be built. It is exciting to think that AAVSO members may soon be involved in the acquisition of *H*-band light curves. Here we can give only some brief hints as to what these light curves will show.

One of the attractive features of an *H*-band photometer is that it will explore largely uncharted territory—very few light curves in *H* have yet been published. The main source of data to date has been the South African Astronomical Observatory—see, for example, Whitelock *et al.* (1991) and Whitelock (2000). The SAAO data are obtained with a *JHKL* photometer, and most of the published light curves refer to the *J* or *K* filters, although the curves in *H* are similar to them in amplitude and phasing. Light curves at a particularly clean narrow-band continuum point at 1.04 μm have been published by Lockwood and Wing (1971). These results can be summarized by stating that the infrared amplitudes are always much smaller than the visual amplitudes—5 times smaller in the case of M-type stars—so that observations at minimum light are usually not much more difficult than observations at maximum. Almost invariably, infrared light curves in *J*, *H*, and *K*, as well as at 1.04 μm, reach maximum about 0.1–0.2 of a cycle later than the visual maximum. The uniformity of these characteristics throughout the wavelengths at which these stars are bright assures us that they must also apply to the bolometric light curve, representing the star's total radiative output. Thus the light curve in *H* should be an excellent indicator of the fundamental variability of the star.

It will also be interesting to compare light curves in *H* to those obtained concurrently by visual observers. The *V-H* color is very sensitive to the temperature, and if we know how much the temperature changes during the course of a cycle, we can calculate how much of the change in brightness is due to diameter changes. Such data will be interesting to compare against direct interferometric measurements of stellar diameters, which are just now starting to become available.

## 6. Summary

Stellar spectra calculated from model atmospheres have been used to show that the photometric *H* band, centered at 1.65 µm, falls in a very special place, at or near the flux maximum in the energy distributions of nearly all stars cooler than the Sun. Not only the opacity minimum of $H^-$ but also a minimum in the absorption spectrum of water make the atmospheres of cool stars more transparent in the *H* band than in any other spectral region. The light in the *H* band therefore comes from deep in the photosphere, and light curves in *H* should reflect the fundamental variations of the star, rather than superficial changes in the strengths of molecular bands.

## 7. Acknowledgements

One of us (Wing) would like to thank the Niels Bohr Institute for hospitality during a visit to Denmark. Many of the ideas concerning the *H*-band photometer, and what can be done with it, have developed during email and teleconference discussions with Doug West, Arne Henden, Janet Mattei, Tom Williams, John Percy, Dan Kaiser, and other members of the AAVSO's Infrared Photometry Working Group.

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