On Improving IR Photometric Passbands

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Abstract

The passbands of the Johnson JHKL broadband photometric system used at a number of major observatories have been compared to the atmospheric window transmissions calculated by MODTRAN, and a family of solar-composition model stellar fluxes from Kurucz (1991 private communication) have been used as input to model the atmospheric extinction under different water vapor content, altitude, and airmass conditions. A figure of merit related to the slope of the extinction curve at zero airmass describes the sensitivity of the response function to atmospheric extinction. We have compared passbands used at several observatories, and have designed an improved set of passbands.

1. Introduction

This paper is a progress report on work undertaken by a Working Group on infrared extinction and standardization of IAU Commission 25, to carry out the recommendations from a two-session meeting of Commissions 25 and 9 at the 1988 Baltimore General Assembly. The work has been carried out primarily at the University of Calgary for the past year, beginning in Fall 1991.

Although most astronomers are difficult to classify, essentially two groups of people participated in that meeting: photometrists who have been wary of working or at least publishing in the infrared because of the difficulties, and a bolder group, who forged ahead and did the best that could be done.

Part of the problem is that there is no generally accepted definition of broadband infrared photometric systems. Although Johnson's (1965) system survives in name, no observer that we know of is actually using anything like his passbands, for the following reasons. The extinction line curves upward in the range $0 < M < 1$, i.e., there is a strong Forbes (1842) effect. Those spectral components that have the highest extinction coefficients are absorbed at very low air masses, leaving only the weaker absorptions to appear at higher airmasses. This is much more severe in the infrared than in the visible part of the spectrum (Milone et al. 1993; Young et al. 1993). Hence, there are systematic variations with water vapor content that cause loss of precision and accuracy, which has led to different attempts to improve matters at each observatory where these effects are noticed. Consequently, there has been a proliferation of passbands, and no single, accepted system.

Bessell & Brett (1989), Glass, and Carter, among others, have by systematic and careful attention to details, been able to wring what was possible from the current

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systems. The general strategy in the past has been to observe at the same dry sites, to reduce the data to standards taken at the same airmass, and to redefine the passbands to better match the transmission windows at particular sites. But this approach has produced site-dependent results that cannot be accurately duplicated elsewhere, particularly at the wetter locations of most telescopes. Here we discuss a new system which we hope will overcome these difficulties.

2. Proposed Global Solution

At the IAU General Assembly joint sessions of Commission 25 and 9 held in Baltimore in 1988, suggestions were put forward which appeared to have strong support among both those present and others who subsequently saw the proceedings (Milone 1989):

1. The passbands should be redesigned to be better centered in the atmospheric windows, and made narrower so as not to be defined by the water vapor absorption bands;

2. The atmosphere should be modeled in real time to better track the extinction variations, thereby partly eliminating the previously unknown variability in the observations due to water vapor variability.

In the simulations carried out to date, we have concentrated on recommendation 1.

In the simulations, we have used 10 stellar atmosphere models from Kurucz (1991) as stellar flux sources, ranging from a 3500 K supergiant to a 35,000 K dwarf, as well as solar and Vega models. For the atmospheric transmission spectra, we have used MODTRAN, a moderate-resolution (1 cm^{-1}) version of LOWTRAN. We have concentrated on the MODTRAN mid-latitude summer and tropical models, which are the wettest ones likely to be met in IR observing, at 1 and 4.2 km (the altitude of Mauna Kea) above sea level. The mid-latitude summer model has about 1.8 cm of precipitable water above 1 km, and the tropical model has about 0.4 cm above 4.2 km. Our extinction-curve model (Young 1989) is

$$m = (a + bM + cM^2)/(1 + dM)$$

where a is the magnitude at $M = 0$, d is effectively $1/M$ at the "corner" of the curve, and b and c may be color-dependent. At $M = 0$, the slope is $b - ad$; at large air masses, m approaches the line $(b/d) + (c/d)M$, plotted as dashed lines in the figures.

Figs. 1 – 5 show simulated extinction curves for two source fluxes. Figs. 1 and 2 are for the original Johnson (1965) K passband. The two atmosphere models differ by a factor of 4.5 in water content, less than the time variations at a single site. If one linearly extrapolates the observable part of the curves outside the atmosphere, the inferred stellar magnitudes vary by more than 0.2 mag, because the water absorption between 0 and 1 airmass is included in the effective passband. Hence, if the water varies during a night, the photometer appears to have an unstable zero-point.

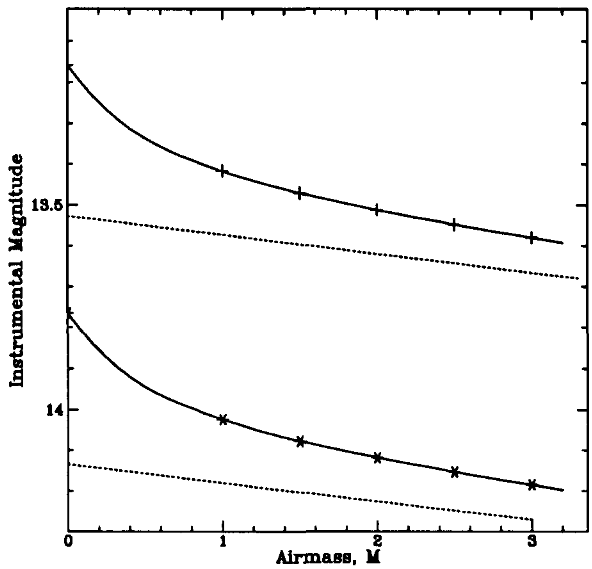

Figure 1 Extinction curves for Johnson's K band at Mauna Kea. The lower curve is for the model atmosphere with 3500 K and log $g = 0$; the upper curve is for T = 5250 K.

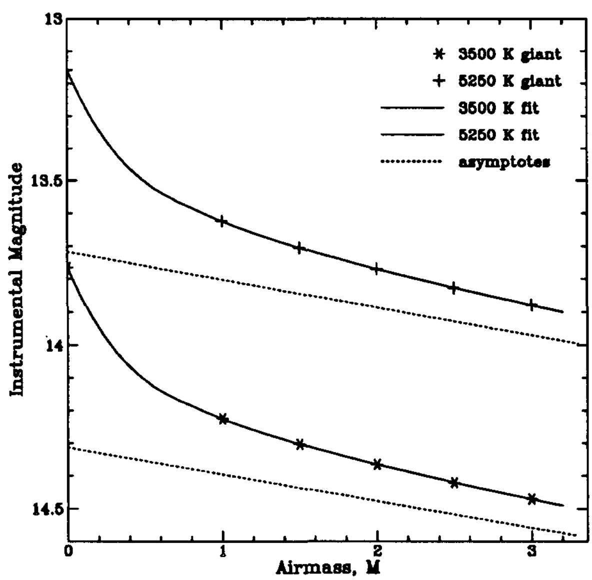

Figure 2 Extinction curves for Johnson's K band at 1 km for midlatitude summer atmosphere.

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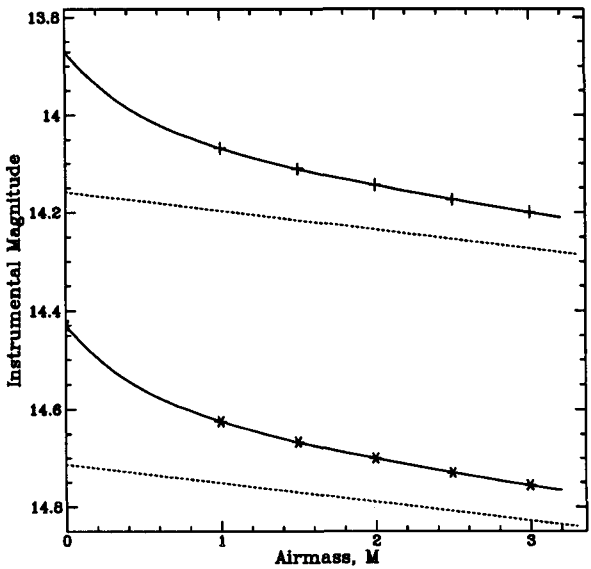

Figure 3 Extinction curves for Wainscoat-Cowie K′ band at Mauna Kea.

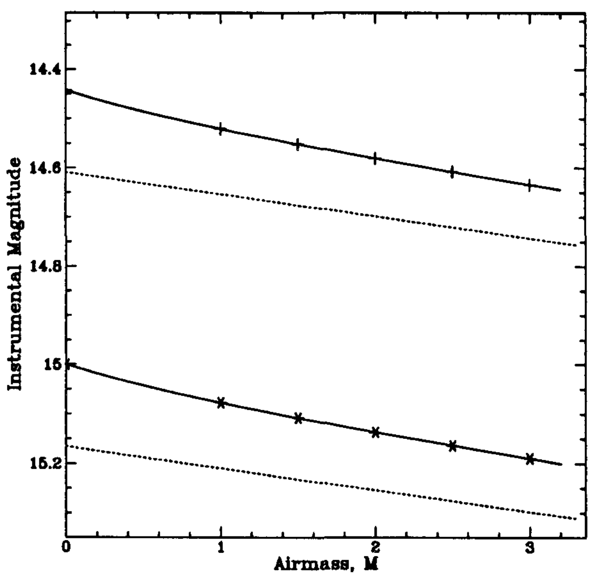

Figure 4 Extinction curves for our recommended K band at 1 km for midlatitude summer atmosphere.

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Fig. 3 shows a similar plot for the K′ filter proposed by Wainscoat & Cowie (1992). Again, the extinction line is strongly curved, and similar instabilities in the measurements result from variable water vapor.

Figs. 4 and 5 are extinction plots for our proposed K replacement for the same two atmospheres as Figs. 1 and 2. The extinction curves for the new filters are nearly linear for both the high- and low-altitude sites. The long-wavelength cutoff of our K passband is similar to that of the Wainscoat-Cowie filter, so we should enjoy a similar freedom from thermal noise. These results promise excellent reproducibility and may well augur a new era of milli-magnitude precision for near-IR passbands in the near future.

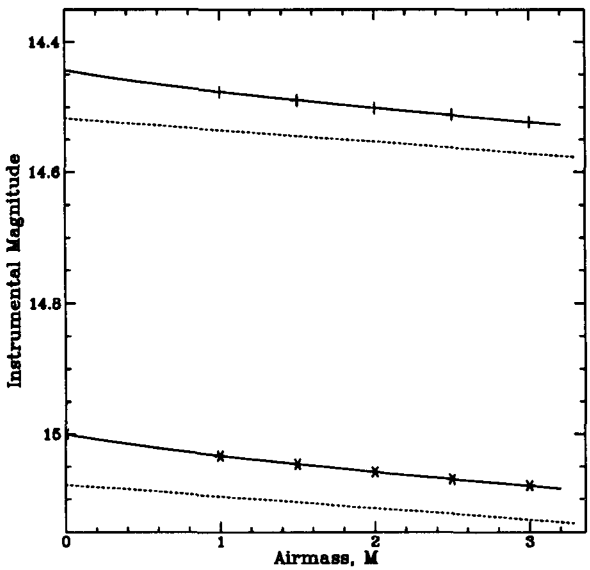

Figure 5 Extinction curves for our recommended K band at Mauna Kea.

The figure of merit that we used to evaluate passbands is the angle θ, by which the stellar spectral irradiance function, regarded as a vector in Hilbert space (Young 1993; Young et al. 1993), is rotated as a consequence of passage through the terrestrial atmosphere. This approach has proven very useful. The θ vs. FWHM relation starts out slowly and then rises rapidly. We try to approach that turning point, within manufacturing tolerances. While decreasing the sky noise, we have kept the filters as broad as possible to maximize flux. Nevertheless, some loss of throughput is inevitable, especially at the higher altitude sites. The benefits are improved transformability and, especially at lower or wetter sites, much improved reproducibility.

We cannot exactly predict expected gains in S/N because of variability in the sky background. We expect substantial improvement from the elimination of portions of older passbands that block source flux and contribute unwanted thermal flux to the detector; but there are non-thermal background sources, such as OH emission from airglow and auroral emission. The airglow may be chopped out in single detector work, but it is not clear what can be done about aurorae, which have spatial and temporal variability on many scales. The airglow is a problem for stare-mode detectors, but by eliminating much of the thermal sky background, we can use longer integrations, so that clear gains in S/N are possible.

The next stage is to test these filters in practice. We expect to obtain a set of filters made to our new specifications in the near future, and should have the first observations early in 1993.

Acknowledgements

We thank Bob Kurucz for providing his model-atmosphere fluxes; Jim Chetwynd at AFGL for recommending MODTRAN instead of LOWTRAN 7; P. Zvengrowski and K. Salkauskas, of the Mathematics Department of the University of Calgary, for helpful discussions with ATY of Hilbert space and functional analysis; Ted Ziajka of the Academic Computer Services of the University of Calgary, for providing ATY with an account on the IBM RS 6000; Barbara McArthur, of the University of Texas, for much assistance with GaussFit; A.W. Harrison and L. Cogger of the Physics and Astronomy Department of the University of Calgary for helpful discussions with EFM on atmospheric emissions; members of the Working Group on Infrared Extinction and Standardization, particularly Ian McLean for commissioning the WG; and M.S. Bessell, T.A. Clark, G. Rieke, and Mike Skrutskie for useful discussions. Roger Heatley of Barr Associates and Mike Larro of OCLI provided much helpful information about interference filters. Sun Kwok assisted with the loan of computer hardware. This project was funded by grants from the University of Calgary Research Grants Committee and the Natural Sciences and Research Council of Canada to EFM, for which we express gratitude.

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Discussion

V. Straizys: *Let me congratulate your working group for making such good order with the infrared photometric systems. It would be nice if a similar order could be made in the visible and the near ultraviolet spectrum.*

Milone: Thank you for the encouragement. There is, of course, less tradition in the IR, and we are most fortunate in getting strong support from a number of people who have done a bit of standardization work with existing systems. In the V-band, a reformation is more difficult to accomplish, but Chris Sterken is working on pairs of filters in the old UBVRI passbands, following suggestions by Andy Young.

R.F. Wing: *you spoke about the filters, but not the detectors. If the filters are wide, the detector plays a role in defining the system. I am worried about the proposed z filter because most detectors which can be used in the one-micron region have a response that either increases or decreases steeply with wavelength. If the z filter is as wide as you propose, observers with different types of detector will be working on different systems. Why not minimize this problem by defining a narrower filter from the outset?*

Milone: Your comment is well taken. There are detectors which are sensitive in this window but probably are not flat here. Most IR people want maximum throughput so one of our constraints has been to maximize this while not sacrificing our primary purpose. We will need to check the effects on transformations of convolutions of our passband with various detectors to see what we can tolerate. Narrowing the filter is certainly one way of responding to it, should the problem appear to be very serious. Keep in touch!

Ian Elliott congratulates Russ Genet on his birthday

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