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Classic and new photometric systems

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Abstract. Many large photometric surveys are based on new or unusual systems. The users of the information they provide need to be aware of certain pitfalls. This paper outlines some of them.
Very often the stated fiducal colours of stars in a given survey are based on modelling from theoretical atmospheres or spectrophotometry rather than actual observational data made with the same set of filters. While models may be satisfactory at the initial stage of data interpretation, for refined studies they may prove inadequate.
The output of a particular detector is dependent, inter alia, on its quantum efficiency, its fore-optics including filters, and the transparency of the Earth's atmosphere. These can virtually never be reproduced exactly between one installation and another. However, for objects with smooth spectra and not suffering severe interstellar reddening, colour transformations are usually reliable between systems with filters having similar central wavelengths and bandwidths.
In studies of extincted regions, such as along the Galactic Plane, the calculation of reddening amounts can depend on detailed filter characteristics and not merely on their "effective wavelengths". Confusion may become significant according to source densities and pixel sizes. In heavily extincted areas, there is a danger of identifying nearby faint sources with distant ones observed at longer wavelengths where the extinction is less. It is therefore necessary to understand the process that is used in cross-correlating the different images when cataloguing colours.

Key words. Stars: standard

1. Introduction

Historically, advances in astronomy have often been linked to the introduction of new technologies enabling surveys to be made to greater depth and at newly-available wavelengths. Each of these brought with them the discovery of new phenomena. Even William Herschel's discovery of the planet Uranus and of physical binaries can be ascribed to what he called 'sweeps' of the sky using his unprecedentedly large telescopes. Recently, we have benefitted from automatic telescopes, large-area detectors, increased sensitivity, larger computers and gigantic on-line databases. The time axis is increasingly available for exploration and all-sky surveys for moving, variable and transient objects are now under way in many locations.

An important area remaining to be explored is *increased precision of measurement*. This is a very obvious concern in the field of astrometry, but is also an important frontier in photometry. A recent example is the improved

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knowledge of small-amplitude variability that has emerged from gravitational lensing surveys such as MACHO, OGLE and the photometric planet and near-earth object searches that are now in progress.

2. Desirable properties of photometric surveys

Though particular surveys may have been set up to address specific questions, it is often found that their long-term usefulness extends in unexpected directions.

2.1. Multiple wavelength coverage

Some surveys are confined to a single wavelength. While this may be all that is required to address a specialized issue such as searching for planetary transits in front of a star, the addition of other wavelengths greatly enhances a survey's value.

The most obvious reason for multi-band surveys is to afford some sort of spectral classification and to identify sources which are unusual. The first successful near-infrared survey, the IRC (Neugebauer and Leighton, 1968), for example, used I and K bands to identify extreme objects, the investigation of which stimulated the whole field of infrared astronomy. Table 1 shows the effective wavelengths used by a few recent and proposed surveys. Even if the filters are sometimes nominally identical between surveys, there can be subtle differences in centre wavelengths and bandwidths. The table shown makes no mention of the filter bandwidths and slopes, which can also affect the usefulness of the photometry derived.

Even variable-object surveys need colour information. The nature of a transient event can often be diagnosed through its behaviour at different wavelengths. As mentioned, unintended uses of survey information often turn out to be as important as their original purposes. Significant advances in the study of 'ordinary' variable stars have arisen from the comprehensive MACHO and OGLE light-curves, such as the period-magnitude relations obeyed by the late-type semi-regulars (Wood, P.R. et al, 1999).

2.2. Precision

Some of the subtlest effects, such as planetary transits, studies of star-spots and high modes of stellar oscillation require very high precision photometry. This places high demands on the stability of instrumental response and atmospheric transparency. Searches for planetary transits, such as PAN-STARRS aim to be able to detect dips as small as 0.01 mag or about one part in 10^4 in the light of a bright star. At this level of precision, the removal of variations due to atmospheric effects requires that comparison objects of similar colour and magnitude to the stars under investigation must be available within the same CCD field so that they can be measured simultaneously.

In addition, global precision in surveys is important for comparison with stellar models. Successful modelling requires that photometric systems be well-understood. Examples are the effects of age and metallicity on the positions of stars in colour-colour and colour-magnitude diagrams, as well as markers such as the level of the Horizontal Branch, the top of the RGB and the position of the Red Clump.

The stated photometric precision of the 2MASS JHK survey, for example, is around 3%. It depends on a table of 65 standard stars with $10 < K < 12$, observed by Persson et al (1998). While the individual stars in this list are stated to have erors of < 0.01 mag, they are sparsely distributed and important regions of the sky, such as the Magellanic Clouds, sometimes depend on a single standard.

2.3. Standard vs non-standard systems

There is much to be said for making surveys in standard colours, as these are easier to interpret than arbitrarily defined ones. Such a choice has to be offset against other considerations, such as using no filter at all, which may be desirable when maximizing the numbers of photons is essential (e.g., the Hipparcos astrometric survey satellite).

An example requiring the use of non-standard filters is the search for brown dwarfs of type T that show hot star colours in the $J - H/H - K$ two-colour diagram, due to ex-

Table 1. Some examples of survey filter bands

Survey name	Instrument	Bands covered
CFHTLS	MEGACAM	u (374), g′(487), r′(625), i′(770), z′(890) nm
SLOAN	own	g′(475), r′(622), i′(763), z′(905), y′(1005) nm
HDF		300, 450, 606, 814 nm
GOODS	Hubble ACS	435, 606, 775, 850 nm
2MASS		1.25, 1.65, 2.16 μm
UKIDSS	WFCAM	Z(0.88), Y(1.02), J(1.25), H(1.64), K(2.20) μm
VISTA	Vista IRC	1.25, 1.65, 2.20 μm
various	Spitzer IRAC	3.6, 4.5, 5.8, 8.0 μm
various	Spitzer MIPS	24, 70, 160 μm
Pan-STARRS	own	"Sloan g,r,i,z,y,w"
LSST		ugrizy
For reference		
Cousins	own	U(365), B(440), V(550), R(670), I(810) nm

traordinary molecular features in their spectra (H_2O, CH_4 and H_2 bands). By adding Y (1.02μm) and Z (0.89μm) to the conventional JHK, the UKIDSS survey (Hewett et al, 2006) removes this degeneracy (see Fig 1).

However, the use of non-standard bands comes at a price. It will require new observations of standard stars whose magnitudes are within the range of the new system, new tables of intrinsic colours, new models, new corrections for interstellar absorption, new z-corrections etc. In any work requiring high precision, these quantities cannot be simply derived from existing standard stars measured through other filters.

The maximum and minimum observable magnitudes at each wavelength must be well understood. Non-linearity of response is a particular problem at the bright end of the range for many detectors. The transmission of the filters and other optical components must be precisely known, as well as the response of the detectors (which may be dependent on previous exposure to bright sources, passage in the case of a satellite through radiation belts etc). The amount and variability of atmospheric extinction also must be characterized.

2.3.1. Transformations and colour equations

Often a very simplistic and trusting attitude is taken to colour equations.

It should be remembered that they are only valid for smooth spectra - i.e., those not affected by deep absorption bands or emission lines. Thus, the colours of e.g, late-type stars cannot be transformed accurately between systems having different filters. For these objects, it is necessary to build up reference libraries of known objects for each new system if they are to be categorised precisely. The colours of Mira variables and other cool stars, being affected by strong and variable intrinsic absorption by, e.g., CO and H_2O, cannot be transformed accurately. QSOs, having strong and variable emission lines, present similar problems. This is not to deny that approximate transformations are possible, if not always completely satisfactory.

2.3.2. Filter concerns

Filters, especially interference filters, cannot be reproduced exactly: some level of manufacturing error has to be tolerated. They have sharp, but not infinitely sharp, cut-on and cut-off wavelengths and may not transmit uni-

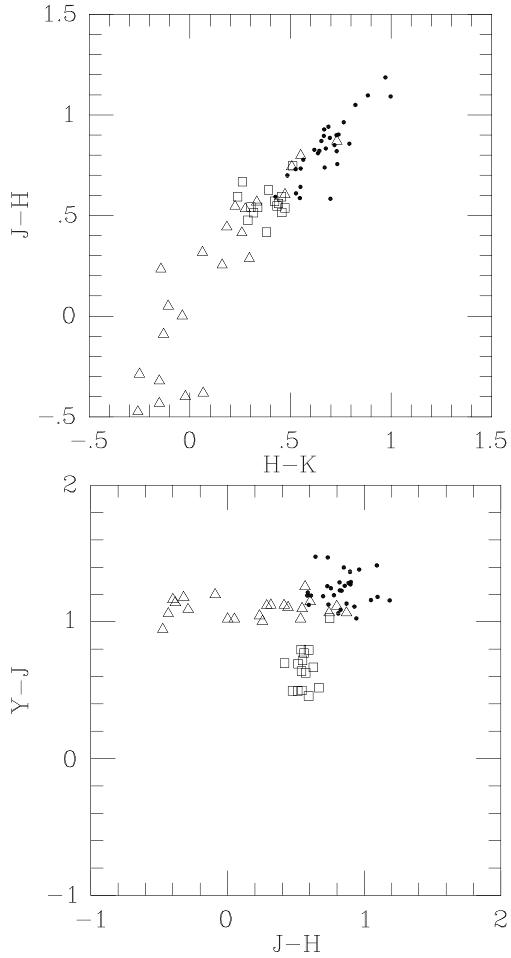

Fig. 1. Colour-colour diagram for M dwarfs (squares), L dwarfs (black dots) and T dwarfs (triangles). Data have been taken from Hewett et al (2006). In the upper diagram, (J–H) vs (H–K), the T-dwarfs occupy the same region (around 0,0) as hot stars, whereas in the (Y-J) vs (J-H) diagram they are distinct.

formly across their passbands. Even within a batch manufactured at the same time there may be small variations.

The effective wavelength of a band is defined to be

$$\lambda_{\text{eff}} = \frac{\int \lambda S(\lambda)\eta(\lambda)d\lambda}{\int S(\lambda)\eta(\lambda)d\lambda},$$

where $\eta(\lambda)$ is the efficiency of the detector and $S(\lambda)$ is the transmission of the filter. The response of the detector to a source having specific intensity $F(\lambda)$ will be

$$R = \text{Constant} \times \int F(\lambda)S(\lambda)\eta(\lambda)d\lambda,$$

which will clearly differ between systems unless all the terms in the equation have the same wavelength dependence [The calibration 'Constant' is determined by observation of a standard star, presumed to have a 'well behaved' $F(\lambda)$].

The equations quoted do not take the earth's atmosphere into account. Many infrared systems have bands whose edges are affected, or even defined, by atmospheric absorption and therefore by its water-vapour content.

It should be remembered that filter characteristics are dependent on their operating temperature, which must be controlled. They may leak outside their nominal transmission region; even a small leak can be disastrous if a source is bright at the wavelength where it occurs. Further, they may degrade with time and change their characteristics, though infrared filters are usually well-protected by being housed under vacuum.

A particular concern for the ultra-large filters required for some survey telescopes being designed is the maintenance of uniform properties across their surface. Precise control of the deposition of the many dielectric layers that they require may be difficult to achieve.

2.4. The Mauna Kea Infrared filter set

The infrared community is particularly aware of filter problems and a few years ago decided to have a large batch of filters made as nearly identical as possible. The "Mauna Kea" filter set covers the bands $JHKK'K_S L'M$. Its JHK filters are narrower than their predecessors to avoid uncertainties in the atmospheric transmission; L' (3.8μm) has replaced L (3.4μm) for the same reason, and K_S omits some thermal background emission in the interests of greater sensitivity (and also the CO first overtone band in late-type stars).

The concepts followed during the design of these filters was endorsed by the IAU in 2000 by the Working Group on IR Photometry and Standard Stars. The filters as actually manufactured have been characterised by Simons & Tokunaga (2002); Tokunaga, Simons & Vacca (2002); Tokunaga & Vacca (2005).

2.5. Effective wavelengths and de-reddening

When the reddening is large, the extinction $A(\lambda)$ may vary significantly across the passband of a broadband filter. In the $IJHK$ region, $A(\lambda) \sim A(V)0.36\lambda^{-1.75}$ mag (approximately). The longest wavelengths passing through the filter may be affected significantly less than the shortest ones when $A(V)$ is very large.

The response of the detector to an extincted source is:

$$R = \text{Constant} \times \int A(\lambda)F(\lambda)S(\lambda)\eta(\lambda)d\lambda,$$

As the form of $A(\lambda)$ may differ from normal in star-forming and certain other regions, it is important that the detector and filter characteristics are known when attempting to de-redden colours, especially if high precision is sought.

The functional form of $A(\lambda)$ in the infrared beyond 2.5 μm changes from a simple power law and appears to flatten out until the region of the SiO absorption bands beyond 8μm. Several recent programmes have lead to better determinations of $A(\lambda)$. (see Nishiyama et al 2006; Naoi et al 2006; Indebetouw et al 2006).

2.6. Spatial resolution, crowding and confusion

Many of the anomalous entries that appear in survey catalogues turn out to be the effect of unresolved observations of more than one object. In addition, in heavily extincted areas, an object that is seen, for example, at K, may not appear at all at visible wavelengths. It may even coincide with a blue object only detected at short wavelengths. Thus, automatic cross-correlation of short and long-wavelength exposures may produce spurious colours. To reduce the chance of such coincidences, the cross-correlation search radius must be as small as possible: determination of spatial coordinates must be appropriately accurate in relation to the space density of objects.

At another level, there must be sufficient space between objects that the sky level can be determined satisfactorily during photometric reductions.

Note

A recent conference 'The future of photometric, spectrophotometric and polarimetric standardization', held in Blankenberge, Belgium, 8–11 May 2006, deals with many of the topics discussed here (See www.vub.ac.be/STER/standards/stds.html for preliminary proceedings).

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