SOME THOUGHTS ABOUT THE PHOTOMETRIC SYSTEM OF GAIA

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ABSTRACT

Some aspects of the photometric mode of a GAIA-like mission are discussed, concentrating on the choice of the passbands (width, location, number) and on the accuracy of the photometric system. The following comments are partly intended as a summary of photometric discussions at the workshop, while partly they reflect some private thoughts about the GAIA photometry.

Key words: GAIA, photometry

1. DETECTORS, WAVELENGTH COVERAGE AND PASSBANDS

As pointed out by several workshop participants, it would be very useful if the wavelength range of the GAIA photometry could be extended to include one or more bands in the near infrared. With the addition of passbands at 1.5 or even 2 microns the photometry would be much less hampered by interstellar extiction; at the same time this extended wavelength baseline would give a much better handle on the classification of the coolest stars.

Although the scientific benefits of an extension towards the infrared are obvious, it is not clear that such a change in the specifications is technically feasible. There is not much that we can do about the long-wave limit of CCD technology, as it is set by the solid state physics of silicon. Moving beyond a wavelength of about one micron therefore means including a fundamentally different type of detector, with different integrating properties, readout electronics and environment requirements. Just to mention one consequence, this may make it impossible to apply the same drift-scan integrating technique that is foreseen for the CCD photometry.

It should also be remembered that at a wavelength of 2 microns, the size of the Airy disk for a 50 cm aperture has increased to about 1 arcsec, which may cause serious crowding problems in the densest parts of the Galactic disk and bulge, i.e., especially in those areas where the advantages of the infrared are most needed. In summary, it is probably fair to say that the addition of infrared channels may be very useful, but cannot be recommended without further detailed study of the technical implications.

In the context of the choice of detectors and wavelength coverage the new ESTEC development of detectors based on superconducting junctions may soon prove to be an extremely competitive alternative. As reported by Perryman & Peacock (1995), these new detectors have nearly 'ideal' properties: quantum efficiency close to unity over the entire wavelength range from UV to near-IR, high time resolution and dynamic range, the possibility of panoramic arrays and, maybe most promising, energy resolution of the order of 0.1–0.01.

The prototype superconducting junction arrays presently under development at ESTEC are still quite modest (36 element arrays with pixels of about 25 microns), but the development may be fast enough to provide a detector array for GAIA. This would open the route to a new and very different kind of spectrophotometry. The energy resolution of the detector would allow low-resolution spectroscopy with an effective wavelength resolution R adjusted to the S/N level of the measurement: from $R = 100$ or higher for the brightest stars to $R = 10$ or less at the faintest levels. Even with R as low as 10 for stars at $V = 14 - 15$ mag we would obtain simultaneous 'multicolour photometry' in about a dozen wavelength bins over the range of 300 to 1000 nm, sufficient for a three-dimensional spectral classification in most cases.

Assuming for the time being that the GAIA photometry will be done with 'classical techniques', using CCDs and filters in the 300–1000 nm wavelength range, what would be the optimum choice of passbands? The photometric system proposed initially for GAIA (cf. Lindegren & Perryman 1994, 1995) was adopted from the system proposed originally for the ROEMER mission (Lindegren et al. 1993). This was basically a modified Stroemgren system, containing the standard uvby and Hβ narrow/wide filters, supplemented with an I band near 800 nm, a near-UV band at 320 nm, and a very wide 'white light' band. Straizys & Hoeg (1995) have proposed an alternative system, the 'Stromvil system', which is a combination of the Stroemgren uvby bands, three bands (at 374, 516 and 656 nm) from the Vilnius photometric system, plus an I-band at 812 nm.

This Stromvil system appears to be a very attractive alternative. First of all, it does not suffer from the problems with small photon numbers in the narrow Hβ filter. Secondly, like the ROEMER system, it provides sensitive three-dimensional classification for most spectral types. Thirdly, it uses a relatively small number (8) of passbands with the right kind of bandwidth (20–30 nm). With this 'right kind of width' I mean the following: sufficiently wide from the point of view of photon statistics and sufficiently narrow from the point of view of sensitivity to spectral details. Furthermore, there is an important practical reason why intermediate bandwidths are to be preferred to wider bands. It is well known that the interpretation of wide-band photometry is plagued by higher order bandwidth effects, i.e., shifts in effective wavelength due to the folding of wide filter profiles with different spectral gradients. These higher order colour terms are proportional to the square of the bandwidth and in typical wide-band colours they can be at the level of 0.01 mag or more. Since the goal of the GAIA photometry is to achieve typical accuracies of 0.001 mag, it would be very unwise to use bandwidths wider than about 1/15 of the effective wavelength.

There are only two amendments to the Stromvil system that I would like to make. Firstly, as has been demonstrated by the five-colour Walraven system, the availability of a second passband in the Balmer continuum is extremely useful. An index for the slope of the Balmer continuum is not only important for the classification of OB-stars, but it also allows better disentangling of temperature and gravity effects in A and early F-stars. Extension of the Stromvil system shortward of the Stroemgren u is therefore strongly recommended.

Secondly, as has been pointed out long ago by Andrew Young, the 'ideal' multicolour photometric system consists of passbands that overlap by about their half-width. Because such a system provides optimum sampling of the stellar energy distribution, it also gives a much better handle on corrections for bandwidth effects and checks on passband stability, as well as improved transformability to other photometric systems. This is particularly true in the wavelength range where the stellar spectral gradients are usually steepest, shortward of about 600 nm. Although in practice it will be difficult to meet this requirement completely in the GAIA photometry, there are no strong constraints in the present GAIA hardware concept that prohibit the use of 12 or even 15 passbands. Apart from the extra passband in the Balmer continuum, I would therefore propose to fill some of the gaps between the Stromvil filters shortward of 600 nm with four or five additional intermediate-width bands.

2. PHOTOMETRIC ACCURACY

A summary of the expected photometric performance of GAIA for an extended Stroemgren system (uvby-Hβ plus three additional bands) can be found in Table 4 of the GAIA document by Lindegren & Perryman (1994). From this table it is clear that millimagnitude photometric accuracy can be obtained with intermediate filter bandwidths (FWHM of 20–30 nm) in the optical wavelength range from a five year GAIA mission for all stars brighter than about $V = 14$ mag. It should be noted, however, that these numbers include averaging of many individual integrations over the five year interval.

Since the study of many different types of stellar variability will be an important goal for the GAIA photometry, it is also instructive to estimate the typical photometric accuracy that can be obtained in an individual integration. In order to do this, I adopt the following values for the relevant system properties: effective telescope aperture: 2×55 cm diameter; transmission of the entire optical train (including filters): 0.5; CCD quantum efficiency: 0.8; filter bandwidth (FWHM): 25 nm; duration of drift scan at 120 arcsec/sec satellite spin rate: 5 sec.

For a typical F or G star, measured near the wavelength of the V band, these numbers correspond to a photometric accuracy per individual 5 sec integration (photon statistics only) of 2 per cent at $V = 15$ mag, 1 per cent at $V = 13.5$ mag, and 0.1 per cent at $V = 8.5$ mag. These numbers are also useful to get some feeling about the systematic accuracy of the GAIA photometric system that should be attainable. Even if the all-sky photometric reference frame for GAIA would be constructed only from those stars that have 0.1 per cent or better accuracy per individual integration, this can be done using all stars brighter than $V = 8.5$ mag. Of such stars there are about 100000 in the sky, which should be more than sufficient to build a dense reference system that is perfectly 'flat' at the level of one millimagnitude. Since the total photometric dataset will be much more extended than this (e.g., about ten million stars with 1 per cent accuracy per integration) it should be possible to establish a reference system with an accuracy well below a millimagnitude.

What does a photometric accurucay of one millimagnitude mean astrophysically? Let us assume that the GAIA photometric system will consist of about a dozen intermediate-width passbands, optimally distributed in the wavelength range of 300–1000 nm. In principle, 0.001 mag photometric accuracy (i.e., 0.0015 mag in the colour indices) then corresponds to the following accuracies in the main stellar photospheric parameters: for a typical B star (around B5V): 15 K in $T_{\rm eff}$ and 0.013 dex in log g; for a typical G star (around G0V): 5 K in $T_{\rm eff}$, 0.015 dex in log g, and 0.008 in [M/H].

It should be noted that 'in principle' here means in the ideal case, i.e., assuming that the interstellar extinction is zero or can be corrected with 0.001 mag accuracy, that calibrating grids of theoretical colours exist that are reliable to this level, and ignoring details such as duplicity and stellar rotation which require more than a simple three-parameter interpretation of the energy distribution. It is clear that for individual stars, accuracies of 0.1 per cent in $T_{\rm eff}$ and about 0.01 dex in surface gravity and metallicity are not always meaningful.

This does not mean, however, that the goal of 'millimagnitude accuracy' should be relaxed! The GAIA photometry will offer the first opportunity to classify stellar spectra in a system that is free of photometric errors over the entire sky down to a level well below the intrinsic 'astrophysical resolution' of the classification. This kind of reliability will be extremely valuable in all studies which require comparisons of accurate spectrophotometry in different parts of the sky. Quite apart from the aspect of spectral classification, the study of stellar microvariability will benefit enormously from a database with muliticolor photometry of unprecedented accuracy for many millions of stars, covering the whole sky during a time interval of five years.

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