IDENTIFYING M SUPERGIANTS WITH GAIA

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ABSTRACT

As a group of stars having high luminosity and thus being able to be detected to great distances, massive M supergiants are extremely helpful to the study of the kinematics of the Milky Way. They are also partly responsible for the creation of post iron-group elements through the weak s-process of nucleosynthesis. As there are relatively few classified M supergiants, owing to their rapid pace of evolution, the identification of additional such stars will serve to significantly increase the sample that can be studied, which offers the promise of a higher fidelity in charting the regions of recent star formation in our Galaxy as well as a fuller description of trends that may be detected amongst their chemical compositions. We discuss the identification of M supergiants using the instrumentation onboard the Gaia satellite, emphasizing the nature of the photometric system that will best serve to classify M stars.

Key words: Gaia; M Stars; Supergiants.

1. INTRODUCTION

Among the most luminous stars in the Milky Way, the M supergiants are massive stars in advanced stages of stellar evolution. Their high luminosity allows them to be detected to great distances, and coupled with their fast pace of evolution they serve to highlight locations of recent star formation in the Galaxy. Thus, a complete census of the M supergiants will aid to produce a galactic map of recent star formation, highlighting the spiral arms and their kinematic properties. Searches for M supergiants are currently underway in select regions of the Milky Way including its core (Comerón et al. 2004). Such studies undertake to locate and classify M supergiants through infrared imaging and low resolution spectroscopy. Their detection through purely photometric means is rendered problematic by interstellar extinction in the galactic plane. A key ingredient for the accurate determination of accurate stellar luminosity is the distance. In principle the distance can be extracted from the photometric and spectroscopic observations providing that the interstellar extinction can be adequately determined.

The M supergiant stars also represent a unique astrophysical laboratory for the study of stellar nucleosynthesis. The weak s-process may be responsible for contributing a fair amount of the post iron-group elements to galactic chemical evolution. The amount and extent of elements produced by the weak s-process depend upon a star's mass and evolutionary phase. Extensive calculations involving nuclear reaction networks (for example, Hoffman et al. 2001; Rauscher et al. 2002; Limongi & Chieffi 2003) for stars more massive than 15 solar masses show the production of a number of isotopes between iron and zirconium during the late phases of helium core burning and beyond. A key question to be answered by observations then becomes one of whether dredge-up has occurred and is sufficiently strong to bring the nuclear processed material to the surface prior to the supernova explosion. The role played by rotation is also important for the pre-supernova development of massive star interiors (Hirschi et al. 2004) and ultimately the amount of pre-supernova material produced by the weak s-process. To our knowledge there has been no discussion on the contraints placed upon the theoretical predictions of the weak s-process and the dredge-up of its by-products by observations of individual massive M stars. (The galactic enrichment of Cu and Zn and the contributors to weak s-process elements in the Sun have been presented by Matteucci et al. (1993).) Our investigations into elemental abundances for α Ori (M2 Iab) (Lundqvist & Wahlgren 2004) uncovered an abundance enhancement for Sr (+1.4 dex), a weak s-process enhanced element, that is similar to that predicted for a star more massive than 15 solar masses.

A hindrance to studies utilizing massive M stars, whether for galactic kinematics or nucleosynthesis, is that relatively few have classifications in the two-dimensional MK system. Accurate classification for both temperature and luminosity is desirable for placement in the HR diagram and comparison with theoretical stellar evolution models for the estimation of their mass. White & Wing (1978) present photometric data for nearly 130 M supergiants having two-dimensional classification, and current sky surveys are detecting other cool luminous stars. With instruments to address the three disciplines of astrometry, photometry and spectroscopy, Gaia will be the ultimate survey tool for stars in our galaxy. It will provide the means to detect and classify cool supergiants, allowing for follow-up observations to be made by high spectral resolution instrumentation for the study of elemental abundances in potential pre-supernova candidates.

2. TRADITIONAL CLASSIFICATION

M supergiants have been identified and classified through both spectroscopic and photometric techniques at optical wavelengths. Spectroscopically, the MK classification system (Keenan1963) accounts for both temperature and luminosity, utilizing spectra of resolutions typically between 1 and 2 Å. The molecular bands of TiO are sensitive indicators of temperature. As one progresses to cooler temperatures from class K to M the first TiO bands to be detected are those at 5167 and 7054 Å. Near spectral class M0 atomic line ratios, such as Ca I (4226) / Fe I (4325) can also be useful indicators of effective temperature. By spectral subclass M2 there are a number of detectable TiO bands that are useful for classification down to temperatures of subclass M5. Later than M5, molecular absorptions from VO help in defining the spectral type. The determination of luminosity class has been established from ratios of spectral line pairs, typically comparing the relative line depth (blackening on photographic plates) of an ion with that from a neutral species. Although these line pairs have historically been established for the blue spectral region, line pairs have been utilized at red and near-IR wavelengths, including a ratio of strong absorption features, Fe(8689)/Fe(8675), that are located within the wavelength interval of the Gaia radial velocity spectrometer (RVS).

The classification of spectral type for M type stars by photometry has been one aspect of the Wing 8-colour narrow-band system (Wing 1971, White & Wing 1978). The placement of its eight filters is designed to measure stellar flux in wavelength regions associated with molecular absorption and the continuum (molecular free). Four of the eight filters are centred at wavelengths (7120, 7540, 7810, 8120) within the sensitivity range of the proposed Gaia detectors. The remaining four filters are located longward of 1 μm. For M type stars, the first filter (λ_c = 7120 Å) measures the absorption from the TiO γ(0,0) band, with possible contamination from CN Δv=+3. The second (λ_c = 7540 Å) and third (λ_c = 7810 Å) filters can be used to measure the continuum, after accounting for possible contaminations arising from CN and TiO, respectively. The fourth filter (λ_c = 8120 Å) is sensitive to the positive luminosity dependence of the molecular CN Δv=+2 band. Therefore, a colour determined from the first two filters, m(7120)–m(7540), measures the strength of the temperature dependence of TiO relative to the continuum, and information about luminosity can be extracted from the flux measured by the fourth filter relative to an estimate of the local continuum. When using all filters of the 8-colour system one acquires a second luminosity index from the CN absorption in the eighth filter (λ_c = 10 975 Å) and a long baseline between filters 2 and 3 to the continuum filter 5 (λ_c = 10 395 Å) for the calibration of effective temperature.

Table 1. Predicted astrometric accuracies for M supergiant ($M_V = -5.0$) with Gaia, for 5-year mission lifetime (no relative parallax error is given if $\sigma(\pi)/\pi$ >1)

V	$E(B-V)=0$			$E(B-V)=2.0$		
	d kpc	$\sigma(\pi)/\pi$	$\sigma(\mu)$ km s^{-1}	d kpc	$\sigma(\pi)/\pi$	$\sigma(\mu)$ km s^{-1}
12	25	0.12	0.05	1.5	<0.01	<0.01
13	40	0.27	0.1	2.3	0.02	<0.01
14	63	0.63	0.3	3.6	0.04	0.02
15	100	–	0.8	5.8	0.09	0.05
16	160	–	1.9	9.1	0.22	0.11
17	250	–	5.0	14	0.57	0.3
17.5	320	–	7.8	18	0.72	0.5
18	400	–	13	23	–	0.8
19	630	–	35	36	–	2.0
20	1000	–	100	58	–	5.9

3. IDENTIFYING M SUPERGIANTS WITH GAIA

All resources of the Gaia mission (astrometry, photometry, and spectroscopy) must be utilized for the confident identification of M supergiants. In addition to accurate distance estimates the Gaia mission is particularly attractive for its relative completeness in sampling the Milky Way and its internal consistency in providing data on stars and a map of the interstellar medium. Astrometric measurements of parallax provide the much desired estimate of distance at an anticipated unparalleled accuracy. However, parallax by itself is not sufficient for identification of M supergiants.

In Table 1 we present astrometric accuracies for stars of spectral subclass M0 and absolute magnitude $M_v = -5.0$, computed using the Gaia astrometric errors from the unpublished technical note GAIA-JDB-008 (de Bruijne 2003). The table presents the Johnson V magnitude, distance, and the astrometric accuracies for the cases of two interstellar reddenings. The error in the proper motion is calculated from the angular proper motion error, assuming that the spatial distance corresponding to the angular error traveled by the star over a five year period. As can be noted from the table, M supergiants will be accessible throughout the Milky Way, depending upon the magnitude of the interstellar extinction.

Gaia photometry provides two supergiant identification techniques.
- In conjunction with the measured parallax, luminosity can be estimated through an observed magnitude and a model for interstellar extinction.
- Fluxes from the medium band system will be used in conjunction with stellar models to derive physical parameters such as effective temperature and luminosity. A translation to spectral type and luminosity class will be possible for studies where comparison with standard star spectra is beneficial.

Eight of the proposed filter systems are displayed, in part, in Figure 1. For M type stars filters can be centered at

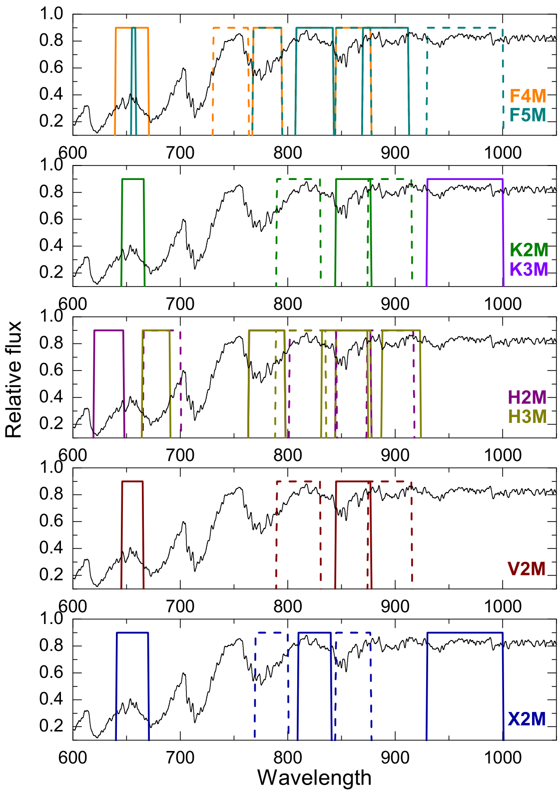

Figure 1. Proposed photometric systems for Gaia are displayed for filters located longward of 600 nm. Eight proposed filter systems (Gaia PWG 2004) are displayed. The K3M system differs from the K2M system in having one additional filter centered at 965 nm. Filters within any one system are portrayed in alternating solid and dashed lines to ease confusion in regions of overlap. None of these systems samples the TiO γ(0,0) band at 712 nm and only one system (F4M) samples the continuum region at 750 nm.

wavelengths that can serve to classify both spectral type and luminosity, in a manner similar to that of the Wing 8-colour system. A significant concern in any direct analogy is provided by the the difference in the filter band widths. The 8-colour system utilizes narrow band filters having FWHM of 50 to 60 Å, while any medium band system for Gaia will be sensitive to a broader spectral region to maximize the number of photons recorded in the limited exposure time. Therefore, the usefulness of the CN band at 8120 Å in the 8-colour system for measurement of luminosity is diminished in Gaia medium band systems by the incursion of TiO and the lack of any redundancy in sampling additional CN bands. This deficiency in the photometric luminosity determination will be more than offset by the astrometric distance determination and any indications of luminosity derived from the RVS data. However, none of the systems presented in Figure 1 sample the broad TiO feature centered near 7120 Å, a feature that is detectable in late-K stars. Four of the systems sample a weaker area of TiO absorption near 7700 Å, but this feature is not useful for the early M type stars and may be contaminated by absorption from CN. Only one system (F4M) samples the high point in the spectrum at 7500 Å, which is a good continuum point for oxygen rich G, K, and M stars. It is therefore desirable to have a medium band system that includes a filter that samples the TiO γ(0,0) system at 7120 Å as well as the continuum area near 7500 Å.

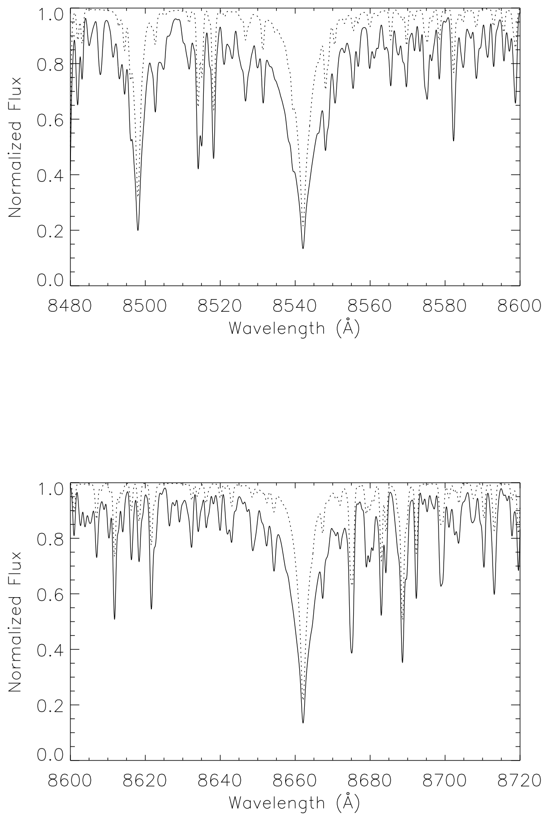

Figure 2. A comparison of synthetic spectra for the supergiant α Ori (M2 Iab, log g = −0.5, solid line) and a giant star with log g = +1.0 (dashed), computed at the Gaia RVS spectral resolution, shows significant differences in the width of lines from the Ca II IR triplet as well as many of the weaker lines. The latter cannot be counted on to be more than a confirmation when S/N levels are very low.

RVS spectroscopy will be obtained at a nominal resolving power of R = 11 500 and will be capable of distinguishing between supergiants and giants. Figure 2 presents a comparison of synthetic spectra for the entire region of the RVS for stars of solar composition and $T_{\rm eff}$ = 3500 K, having the gravity of a supergiant and a luminous giant. The calculation was performed using the ATLAS/SYNTHE suite of programs, models, and line data (Kurucz 1993). Lines of the Ca II IR triplet are noticeably broader in the supergiant, and there also exist notable differences in the depths of many features. This region is devoid of any significant molecular absorption for early and mid M type stars, which excludes any potential benefits to luminosity classification from the CN molecule. In general, synthetic spectrum modelling of the RVS data will complement and provide a check for the determination of effective temperature, luminosity and chemical composition as derived from the astrometric and photometric data. The ability to use the Ca II line profiles a luminosity indicator will not be as adversely affected by low counts (low S/N) as the determination of elemental abundances, which are reliant upon weaker features.

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