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GETTING THE RED OUT: A STELLAR APPROACH TO DETERMINING SPATIAL VARIATIONS OF INTERSTELLAR DUST

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RESUMEN

Utilizando dos técnicas espectroscópicas diferentes hemos hecho un mapa de la variación de la extinción interestelar debida a polvo, que se origina en el cúmulo globular M4. Encontramos un enrojecimiento promedio $E(B-V)$ de 0.33 ± 0.01 y $R = 3.4 \pm 0.4$. Ambos valores concuerdan con estudios anteriores de M4. Para estrellas individuales en las regiones más enrojecidas de M4, encontramos valores de $E(B-V)$ que son mayores que aquellos inferidos en estudios de gas interestelar — para regiones muy enrojecidas, la determinación del gas a partir de mediciones de la densidad de columna puede no trazar fielmente al polvo.

ABSTRACT

By employing two different spectroscopic techniques we have mapped out the variable ISM dust extinction endemic to globular cluster M4. We derive an average $E(B-V)$ reddening of 0.33 ± 0.01 and $R = 3.4 \pm 0.4$, both in good agreement with previous studies of M4. For individual stars in the most heavily reddened regions of M4, we find $E(B-V)$ values significantly higher than those inferred by studies of interstellar gas — for heavily reddened regions, the gas measured in column density measurements may not completely trace the dust.

Key Words: **GLOBULAR CLUSTERS: GENERAL — GLOBULAR CLUSTERS: INDIVIDUAL (NGC 6121)— ISM: DUST, EXTINCTION — ISM: STRUCTURE — STARS: FUNDAMENTAL PARAMETERS**

1. INTRODUCTION

How much light from a particular astronomical source is attenuated due to intervening dust? How does the dust obscuration vary on spatial scales? How well do standard techniques used for studying interstellar gas infer the reddening due to dust along a particular line of sight? Using observations of individual stars in globular cluster M4, we have developed a technique which directly recovers the intrinsic reddening information of the intervening dust.

M4 is essentially the closest globular cluster, located at a distance of roughly 2 kpc. The line of sight to M4 passes through the outer parts of the Scorpius–Ophiuchus dark cloud complex, which lies ∼150 to 250 pc (Cudworth & Rees 1990) from the Sun. Visual extinction is high, making this region exceptionally difficult to study in the optical. The interstellar reddening in this region is also differential; the reddening varies across the face of M4 (Cudworth & Rees 1990; Liu & Janes 1990; Minniti, Coyne & Claria 1992). And, the dust extinction probably varies on small spatial scales as well. This is suggested by the scatter in the color–magnitude diagram of M4 (see Figure 1): the subgiant and giant branches are much broader than can be attributed to photometric uncertainties. In this paper, we describe a stellar approach to deriving $E(B-V)$ and R $[R \equiv E(V-K)/E(B-V) = A_V/E(B-V)]$ for this cluster using high resolution ($\Delta\lambda/\lambda$ = 50-60,000) data taken with cross–dispersed spectrographs at the Lick (Vogt 1987; Valenti, Butler & Marcy 1995) and McDonald Observatories (Tull et al. 1995).

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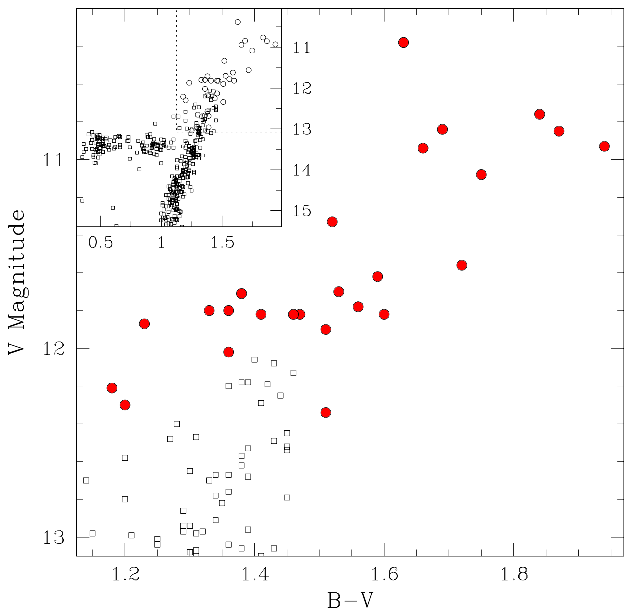

Fig. 1. A color–magnitude diagram of M4, with photometry from Cudworth & Rees (1990) showing the positions of our program stars in solid circles. The inset diagram shows the program stars with respect to all of the Cudworth & Rees (1990) M4 stars of magnitude ≤ 15.5.

2. STELLAR PARAMETERS

We combined traditional spectroscopic abundance methods with modifications to the line–depth ratio technique pioneered by Gray (1994) to determine the atmospheric parameters of our stars. The "Gray" method relies on ratios of central depths of carefully selected absorption features which have different functional dependences on effective temperatures (e.g. vanadium versus neutral or ionized iron; see Gray 1994, table 2) to derive accurate relative temperature rankings . Gray's work was done on main sequence stars similar to the Sun in metallicity and has since been expanded by Hiltgen (1996) for applications to subgiants of a range of disk metallicities. Happily, many of Gray's line depth ratios are also sensitive T_{eff} indicators for lower metallicity very cool red giant branch (RGB) stars. Within most clusters, there is no evidence that there may be any important variations in star–to–star abundances of the elements producing the temperature–sensitive lines. The line depth ratios vary more than one dex in spectra of giants of moderately metal–poor clusters, and thus can indicate very small T_{eff} changes.

Our initial T_{eff} calibration of the M4 line depth ratios was set through a similar analysis of RGB stars of M5. M5 is a cluster of very similar metallicity but suffers from little interstellar dust extinction. The details of the correlations and transformations are discussed in Ivans et al. (1999; §3). In brief, we derived fits of the measured ratios in M5 stars to their temperatures and colour indices. We then inverted the relations to predict relative T_{eff}s in our M4 stars using the M4 line depth ratios. That is, the "Gray" method permitted us to accurately rank our stars using M5 as the temperature calibrator. Then, we relied on a full spectral analysis to determine the actual M4 star temperatures. Subsequent iterations of the models yielded final T_{eff}s that were obtained by ensuring that no trends of abundances were derived from individual Fe I lines as a function of the excitation potentials of the individual lines. Combining the two spectroscopic methods permitted us to bypass the difficulties inherent in using the M4 $B-V$ photometry to determine the model atmosphere parameters.

3. DISENTANGLING THE DUST

Taking advantage of the non–photometric means by which we obtained our temperatures, we estimated the intrinsic $B-V$ colours by interpolating the model atmosphere predictions of Cohen, Frogel & Persson (1978) and subtracting these intrinsic $B-V$ colours from the observed colors. The results for individual stars can be found in Ivans et al. (1999; §3). We then made star–by–star comparisons of our results against $E(B-V)$ estimates derived independently in interstellar absorption studies of potassium by Lyons et al. (1995).

For three particular stars, our reddening estimates are significantly higher than those derived by Lyons et al. (1995). These stars are in the western half of the cluster, the most heavily reddened region of M4, according to previous differential reddening results (§1) and a region on the sky for which higher than average IRAS 100 μm flux values have also been measured. The stars we observed nearest to these in the sky also have relatively high reddening values. It may simply be that the gas measured in the K I column density measurements — the basis of the Lyons et al. (1995) reddening estimates — does not completely trace the dust or the IRAS flux measurements, due to shielding effects and variations in the optical depth of the gas as suggested by de Geus & Burton (1991) in their study of the Sco–Oph molecular cloud region. With the exception of the values derived for stars in the region of highest IRAS fluxes, where standard interstellar methods seem to underestimate the values, the agreement for the remainder of the stars in common is excellent: $\langle \delta E(B-V) \rangle = +0.01 \pm 0.01$ magnitude ($\sigma = 0.05$ magnitude).

Our average $E(B-V)$ reddening of 0.33 ± 0.01, while in good agreement the M4 RR Lyrae studies by Caputo et al. (1985; $E(B-V) = 0.32$–0.33), is significantly lower than that estimated by using the dust maps made by Schlegel et al. (1998). The difference is $\langle \delta E(B-V) \rangle = -0.17 \pm 0.01$ magnitudes ($\sigma = 0.04$ magnitude). Similar differences have been found for the Taurus dark cloud complex (Arce & Goodman 1999) and for galaxy WKK5345 (Woudt 1998), close to the galactic plane. Arce & Goodman attribute the cause of the dust opacity estimate discrepancy to the correlation of intrinsic $E(B-V)$ and Mg_2 assumed by Schlegel et al., which produces an overall overestimate of reddening values in regions of large extinction.

In addition to large and differential reddening in M4, there is evidence that the dust along the line of sight has anomalous absorption properties that deviate from the "normal" law of interstellar extinction described by R values in the range of 3.0 to 3.1 (Harris 1973; Barlow & Cohen 1977; Sneden et al. 1978). Studying the outer parts of the Sco–Oph dust cloud complex, Chini (1981) determined $R = 4.2 \pm 0.2$ in this region of the sky. Cudworth & Rees (1990) found $R = 3.3 \pm 0.7$. Work done by Clayton & Cardelli (1988) gives $R = 3.8$ for σ Sco, a star only one degree in the plane of the sky away from M4. Many other investigations, with similar, high R results, are reviewed by Dixon & Longmore (1993).

To examine this issue, we determined the intrinsic $V-K$ colours by interpolating the model atmosphere predictions of Cohen et al. (1978) and comparing the predicted values against the un–dereddened observations of Frogel, Persson & Cohen (1983). Combined with our derived $E(B-V)$ values, we obtained a value of $R = 3.4 \pm 0.4$, in reasonable agreement with that of previous M4 studies.

4. SUMMARY, DISCUSSION, AND FUTURE WORK

Confronted with a cluster having large and variable interstellar extinction across the cluster face, we combined traditional spectroscopic abundance methods with modifications to the line–depth ratio technique pioneered by Gray (1994) to determine the atmospheric parameters of our stars. We derive a total–to–selective extinction ratio of 3.4 ± 0.4 and an average $\langle E(B-V) \rangle$ reddening of 0.33 ± 0.01, in good agreement with previous M4 studies but significantly lower than that estimated by using the dust maps made by Schlegel et al. (1998).

We find that the gas measured in the gas column density measurements seems to underestimate the dust contribution in regions of large reddening. In the case of M4, the stellar approach probes a larger dynamic range of reddening values than interstellar absorption line techniques yield. However, because our technique relies on the broad-band photometry, our approach does not yield information about individual reddening components along the line of sight. Thus, for studies of interstellar dust, the stellar approach cannot supplant the techniques of studying interstellar gas, but does complement them.

A comprehensive investigation of the spectroscopic line ratios of other globular clusters, utilizing high resolution data, is underway and results will be reported in a future publication.

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