DISCOVERY OF A PROBABLE CH STAR IN THE GLOBULAR CLUSTER M14 AND IMPLICATIONS FOR THE EVOLUTION OF BINARIES IN CLUSTERS

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ABSTRACT

We report the discovery of a probable CH star in the core of the Galactic globular cluster M14 (= NGC 6402 = C1735−032), identified from an integrated-light spectrum of the cluster obtained with the MOS spectrograph on the Canada-France-Hawaii telescope. From a high-resolution echelle spectrum of the same star obtained with the Hydra fiber positioner and bench spectrograph on the WIYN telescope, we measure a radial velocity of \( -53.0 \pm 1.2 \) km s\(^{-1}\). Although this velocity is inconsistent with published estimates of the systemic radial velocity of M14 (e.g., \( v_r \approx -123 \) km s\(^{-1}\)), we use high-precision Hydra velocities for 20 stars in the central 2/6 of M14 to calculate improved values for the cluster mean velocity and one-dimensional velocity dispersion: \( -59.5 \pm 1.9 \) km s\(^{-1}\) and \( 8.2 \pm 1.4 \) km s\(^{-1}\), respectively. Both the star’s location near the tip of the red giant branch in the cluster color-magnitude diagram and its radial velocity therefore argue for membership in M14. Since the intermediate-resolution MOS spectrum shows not only enhanced CH absorption but also strong Swan bands of C\(_2\), M14 joins \( \omega \) Cen as the only globular clusters known to contain “classical” CH stars. Although evidence for its duplicity must await additional radial velocity measurements, the CH star in M14 is probably, like all field CH stars, a spectroscopic binary with a degenerate (white dwarf) secondary. The candidate and confirmed CH stars in M14 and \( \omega \) Cen, and in a number of Galactic dSph galaxies, may then owe their existence to the long timescales for the shrinking and coalescence of hard binaries in low-concentration environments.

Subject headings: binaries: general — galaxies: stellar content — Galaxy: stellar content — globular clusters: individual (M14) — Local Group — stars: carbon

1. INTRODUCTION

Among the presently known types of carbon stars, only the CH stars have abundances and kinematics that are indicative of membership in the Galactic halo (McClure 1985). Since stars of mass \( M \approx 0.8 \, M_\odot \) are not thought to experience the third dredge-up mechanism during their ascent of the asymptotic giant branch (AGB) (e.g., Iben 1975), the origin of the enhanced abundances of carbon and s-process elements in these giants remained a puzzle until the discovery that all field CH stars are binaries composed of a red giant primary and a degenerate (i.e., white dwarf) secondary (McClure 1984; McClure & Woodsworth 1990). The peculiar abundances of these objects are therefore thought to be the result of mass transfer via stellar winds or Roche lobe overflow during the ascent of the white dwarf progenitor up the AGB (Han et al. 1995). Clearly, the discovery of globular cluster CH stars would have important implications not only for nucleogenesis and globular cluster abundance anomalies (Pilachowski et al. 1996), but also for the formation, evolution, and destruction of binaries in dense environments (Hut et al. 1992).

However, searches for CH stars in several globular clusters based on spectroscopic surveys of brightest cluster members (Harding 1962), direct imaging through intermediate-band filters (Palmer 1980; Palmer & Wing 1982), and transmission-grating slitless spectroscopy (Bond 1975) have proved, by and large, unsuccessful. At present, a handful of stars having enhanced carbon and s-process elements have been reported in each of \( \omega \) Cen (e.g., Harding 1962; Dickens 1972; Bond 1975), M22 (Hesser, Hartwick, & McClure 1977; McClure & Norris 1977; Hesser & Harris 1979), M55 (Smith & Norris 1982), and M2 (Zinn 1981). However, while the spectra of these stars are characterized by abnormally high CH absorption compared to other cluster giants, they usually do not show strong Swan bands of C\(_2\), suggesting that their anomalous carbon abundances probably arise through a different mechanism, such as incomplete CN processing (Vanture & Wallerstein 1992), than that operating in “classical” CH stars. Indeed, among this sample of CH-enhanced stars in globular clusters, only two are likely to be genuine CH stars. Both of these stars, RGO 55 (Harding 1962) and RGO 70 (Dickens 1972), are found in \( \omega \) Cen.

In this Letter, we report the serendipitous discovery of a carbon star in the core of the poorly studied globular cluster M14 and argue that it is likely to be a “classical” CH star: a post–mass transfer binary consisting of a red giant primary and a white dwarf secondary (McClure & Woodsworth 1990).
2. OBSERVATIONS

2.1. MOS Spectroscopy

During an observing run in 1996 May intended to measure radial velocities and Mg b line strengths for globular clusters surrounding the supergiant elliptical galaxy M87, we used the MOS imaging spectrograph on the Canada-France-Hawaii Telescope (CHFT) to obtain long-slit comparison spectra of the integrated light of several Galactic globular clusters. During the integrations, the telescope was allowed to drift, typically through a spatial extent of about 1\′′, in a direction (south to north) perpendicular to the slit in order to generate a spectrum representative of the integrated light of the cluster. All spectra were accumulated using the B400 grism and STIS2 CCD, which combine to give a dispersion of 3.6Å pixel\(^{-1}\) and a resolution of \(3.8\)Å. A blocking filter was used to restrict the wavelength region to 4500–5700Å.

Unexpectedly, the long-slit spectrum of the integrated light of the Galactic globular cluster M14, obtained on 1996 May 19, showed strong Swan bands of C\(_2\), indicating the presence of a carbon star in the cluster core. Because of the drift-scanning technique employed, the immediate identification of the carbon star was in some doubt. By good fortune, however, the carbon star has few bright neighbors to the north or south, allowing a probable identification of the candidate based on its east-west position (see Fig. 1 [Pl. L1]). On 1996 May 20, we obtained a 600 s spectroscopic exposure of the suspected carbon star, using a 1\′\,\,300\,\,300 slit. The blocking filter was removed to extend the spectral coverage to the region 4000–8000 Å. After standard pre-processing, the carbon star spectrum was traced, extracted, and wavelength calibrated using IRAF.\(^8\) The final spectrum is shown in Figure 2.

2.2. MOS Photometry

Of the three published color-magnitude diagrams (CMDs) for M14 (e.g., Smith-Kogon, Wehlau, & Demers 1974; Shara et al. 1986; Margon et al. 1991), only the photographic study of Smith-Kogon et al. (1974) includes stars brighter than the cluster horizontal branch. Unfortunately, these authors did not publish magnitudes, colors, or finding charts for their program stars. Therefore, to determine the location of the carbon star in the cluster CMD, we obtained a number of \(B\) and \(V\) images of M14 using MOS on 1996 May 19 and 22 (Fig. 1). All frames were then reduced using DAOphot II (Stetson, Davis, & Crabtree 1990). Empirically, we found that the CMD based on the two poorest seeing frames (FWHM \(\approx 1.1\)) exhibited less scatter, reflecting the severe MOS undersampling (0′.44 pixels) in the other frames. Our instrumental magnitudes were then calibrated using eight unsaturated local photoelectric standard stars (Smith-Kogon et al. 1974). These stars span a magnitude range of 12.46 \(< V < 14.59\) and a color range of 1.17 \(< B - V < 2.05\). The internal random errors in the calibration are approximately 0.02 in \(V\) and approximately 0.04 in \((B - V)\).

2.3. Hydra Spectroscopy

Although the carbon star’s small offset of 13′′8 \(\approx 0.3r\), from the cluster center (Shaw & White 1986; Trager, King, & Djorgovski 1995) and its position near the tip of the cluster red giant branch (see Fig. 3) suggest that it is physically associated with the cluster, radial velocities for both the carbon star and M14 are needed to provide unambiguous evidence of membership.\(^9\) In particular, radial velocities are needed to eliminate the possibility that the object is a carbon-rich dwarf residing in the solar neighborhood (e.g., Green et al. 1994), although the a priori probability of this is low: to a limiting magnitude of \(V = 18\), the surface density of faint, high-

\(^8\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

\(^9\) For instance, RGO 153, a carbon star that lies only 18′, or 7r, (Trager et al. 1995), from the center of \(\alpha\) Cen, was shown by Smith & Wing (1972) to have a radial velocity that differs from that of the cluster by more than 250 km s\(^{-1}\). For comparison, the confirmed member CH stars, RGO 55 and RGO 70, are located 9′ and 19′, respectively, from the cluster center.
latitude carbon stars (of which dwarf carbon stars make up about 13\%) is approximately 0.02 deg$^{-2}$ (Green et al. 1994). Moreover, the MOS spectrum (Fig. 2) shows only a weak C\_2 band head at 6191 Å, a feature that Green et al. (1992) suggest to be unusually strong in the spectra of dwarf carbon stars. Finally, if the star in question were a nearby dwarf, it might be expected to show a measurable proper motion. Comparison of our CFHT images with a photographic plate taken in 1952 with the Mount Wilson Telescope (see Fig. 1 of Wehlau & Froelich 1994) shows no evidence for such a proper motion.

On 1996 July 18–19, we used the Hydra fiber positioner and bench-mounted echelle spectrograph on the WIYN Telescope to measure 505 radial velocities (median precision $\approx 1.3$ km s$^{-1}$) for 493 stars in a $\approx 0.5$ deg$^2$ field centered on M14. In the course of this survey (Côté & Welch 1997), we also obtained an 1800 s spectroscopic exposure of the M14 carbon star at a resolution $\approx 0.33$ Å over the spectral range 4983–5252 Å. After the program spectra were traced, extracted, and wave-length-calibrated using IRAF, they were cross-correlated against a template spectrum of HD 223094, a K5 III radial velocity standard. In the case of the carbon star spectrum, the adopted template was HD 156074, an R star that is known to have a constant heliocentric radial velocity of $-12.99$ km s$^{-1}$ (McClure 1996).

3. DISCUSSION

3.1. Membership

From our Hydra spectrum of the carbon star, we measure a radial velocity of $v_r = 53.0 \pm 1.2$ km s$^{-1}$ (Heliocentric Julian Date $= 2450282.761$). How does this compare to the systemic velocity of M14? Available radial velocity measurements for this cluster have been reviewed by Webbink (1981), who quotes a weighted mean velocity of $v_r = -123 \pm 5$ km s$^{-1}$. This value is based primarily on low-dispersion spectra of the integrated cluster light obtained by Mayall (1946), as well as a small number of radial velocities (spanning the range 9 to $-153$ km s$^{-1}$) for four type II Cepheid stars in the field of M14 accumulated by Joy (1949). An image-tube spectrogram obtained by Hesser, Shavel, & Meyer (1986) of the integrated cluster light yielded a radial velocity of $v_r = -25 \pm 14$ km s$^{-1}$. Given the obvious difficulties with field star contamination in this direction ($l = 21^\circ.3$, $b = 14^\circ.8$), as well as the large uncertainties of the Mayall (1946) velocities (typical internal error $\approx 33$ km s$^{-1}$, but potentially much larger external errors; see Hesser et al. 1986), we have used our new sample of Hydra velocities to determine improved estimates of the systemic velocity and internal dispersion of M14.$^{10}$

We define a sample of probable M14 members by restricting ourselves to those stars that lie within two half-light radii $r_H$ of the cluster center (i.e., $2r_H \approx 2\,2\,6$; Trager et al. 1995). This sample consists of 20 stars that have a median velocity uncertainty of 1.2 km s$^{-1}$ and span the range $-72.0 \leq v_r \leq -47.6$ km s$^{-1}$. BV$^r$ photometry for these stars (see Fig. 3) demonstrates that they are all likely to be cluster members, since they define a smooth red giant branch extending from $V = 14.38$ to 16.23. From this sample, we find a mean velocity of $v_r = -59.5 \pm 1.9$ km s$^{-1}$ and a one-dimensional cluster velocity dispersion of $\sigma_v = 8.2 \pm 1.4$ km s$^{-1}$ using the maximum likelihood estimators of Pryor & Meylan (1993). Based on the close agreement between the radial velocity of the carbon star and that of M14, we conclude that the star is indeed a cluster member. We also note that if the star in question is similar to the field CH stars studied by McClure & Woodsworth (1990), then an additional velocity component due to the orbital motion of the giant primary around the center of mass of the system is expected; among the eight CH stars monitored by McClure & Woodsworth (1990), the velocity semi-amplitudes ranged from 4.3 to 12.1 km s$^{-1}$, with a mean of 8.1 km s$^{-1}$.

3.2. Implications

Radial velocity surveys of field CH stars have provided compelling evidence that all of these systems are post–mass transfer binaries. We therefore conclude that the carbon star in M14 is very likely to be a spectroscopic binary having a white dwarf secondary, although confirmation of duplicity must await additional radial velocity measurements.$^{11}$ It is perhaps notable that as the only two clusters known to contain candidate or confirmed CH stars, M14 and ω Cen are both massive, low-concentration systems. A possible connection between cluster concentration and CH enhancement was noted previously by McClure & Norris (1977), who, in a prescient remark, suggested that “searches for CH stars in the low-concentration clusters M14 and NGC 2419 might be profitable.”

Does environment play a role in the evolution of globular cluster CH stars? The dominant dynamical processes affecting binaries in globular clusters are the disruption of “soft” binaries through stellar encounters and the shrinking of the orbits of “hard” binaries via energy exchanges with intruder stars (e.g., Hut et al. 1992). Equation (1) of Hills (1984) can be used to estimate the separation, $a_0$, of the widest cluster binaries that are expected to have escaped disruption over a Hubble time. Since most Galactic globular clusters have three-dimensional velocity dispersions $\sigma_v \approx 15$ km s$^{-1}$ (Pryor & Meylan 1993), we find $a_0 \approx 6$ AU. This is comparable to the separation of the widest binaries in the McClure & Woodsworth (1990) sample of field CH stars (i.e., $1 \leq a \leq 4.5$ AU). Therefore, we conclude that the process of CH star disruption is unlikely to be important for most clusters.

On the other hand, the shrinking of hard binaries may play a more significant role. At the cluster center, intruder stars will shrink the orbits of hard binaries at the rate

$$\frac{d \ln a}{dt} \approx \frac{-2 \pi G \rho_c}{\sigma_v},$$

where $a$ is the semimajor axis of the binary, $\sigma_v$ is the central one-dimensional velocity dispersion, and $\rho_c$ is the central mass density (Hills 1984; Phinney 1996). Integration of this equation yields the initial semimajor axis $a_0$ of the binary, whose size is halved over the lifetime, $t_o$, of a cluster:

$$a_0 = \frac{\sigma_v}{2 \pi G \rho_c t_o}.$$
The orbits of hard binaries that are initially wider than this shrink rapidly and have $a \approx a_1$ after a Hubble time. Conversely, tighter binaries evolve on rather longer timescales and are largely unaffected. Thus, $a_1$ is the characteristic final separation of surviving cluster binaries (Phinney 1996). It is worth bearing in mind, however, that equation (2) refers to the cluster center; the situation for the cluster as a whole is undoubtedly more complicated.

In Figure 4 we plot the distribution of $a_1$ against absolute magnitude, $M_T$, for Galactic globular clusters (filled circles) and dSph galaxies (open squares). The dashed line shows the semimajor axis of the shortest period binary in the McClure & Woodsworth (1990) sample of field CH stars (i.e., $a \approx 1$ AU). M14 and $\omega$ Cen are shown as open stars. Based on its location in this diagram, NGC 2419 is a prime candidate for a search for CH stars.

The discovery of a CH star in M14 therefore provides additional support for the notion (McClure 1984) that the process of CH star formation depends on environment, in particular, on the rate of hard binary shrinking through stellar encounters. Given the incomplete and inhomogeneous nature of existing surveys for CH stars in globular clusters, a renewed effort to discover such objects in an expanded sample of clusters (particularly those objects that lie above the dashed line in Fig. 4) may provide new insights into the influence of environment on binary evolution.

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REFERENCES

Aaronson, M., & Olszewski, E. W. 1987, AJ, 94, 657
Armandroff, T. E., Olszewski, E. W., & Pryor, C. 1995, AJ, 110, 2131
Bond, H. E. 1975, ApJ, 202, L47
Boothroyd, A. L., & Sackman, I. J. 1988, ApJ, 328, 632
Côté, P., & Welch, D. L. 1997, in preparation
Dickens, R. J. 1972, MNRAS, 159, 7P
Djorgovski, S. G. 1993, in The Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski & G. Meylan (San Francisco: ASP), 373
Green, P. J., Margon, B., Anderson, S. F., & Cook, K. 1994, ApJ, 434, 319
Green, P. J., Margon, B., Anderson, S. F., & MacConnell, D. J. 1992, ApJ, 400, 629
Han, Z., Eggleton, P. P., Podsiadlowski, P., & Tout, C. A. 1995, MNRAS, 277, 1443
Harding, G. A. 1962, Observatory, 82, 205
Hesser, J. E., & Harris, G. L. H. 1979, ApJ, 234, 513
Hesser, J. E., Hartwick, F. D. A., & McClure, R. D. 1977, ApJS, 33, 471
Hesser, J. E., Shawl, S. J., & Meyer, J. E. 1986, PASP, 98, 403
Hills, J. G. 1984, AJ, 89, 1811
Hut, P., et al. 1992, PASP, 104, 981
Iben, I. 1975, ApJ, 196, 525
Irwin, M., & Hatzidimitriou, D. 1995, MNRAS, 277, 1293
Joy, A. H. 1949, ApJ, 110, 105
Margon, B., Anderson, S. F., Downes, R. A., Bohlin, R. C., & Jakobsen, P. 1991, ApJ, 369, L71
Mayall, N. U. 1946, ApJ, 104, 290
Mayor, M., Duquennoy, A., Udry, S., Andersen, J., & Nordström, B. 1996, in The Origins, Evolution, and Destinies of Binary Stars in Clusters, ed. E. F. Milone & J.-C. Mermilliod (San Francisco: ASP), 190
McClure, R. D. 1984, ApJ, 280, L31
———. 1985, in Cool Stars with Excesses of Heavy Elements, ed. M. Jaschek & P. C. Keenan (Dordrecht: Reidel), 315
———. 1996, in IAU Symp. 177, The Carbon Star Phenomenon, ed. R. F. Wing (Dordrecht: Reidel), in press
McClure, R. D., & Norris, J. 1977, ApJ, 217, L101
McClure, R. D., & Woodsworth, A. W. 1990, ApJ, 352, 709
Palmer, L. G. 1980, Ph.D. thesis, Ohio State Univ.
Palmer, L. G., & Wing, R. F. 1982, AJ, 87, 1739
Phinney, E. S. 1996, in The Origins, Evolution, and Destinies of Binary Stars in Clusters, ed. E. F. Milone & J.-C. Mermilliod (San Francisco: ASP), 163
Pilachowski, C. A., Sneden, C., Kraft, R. P., & Langer, G. E. 1996, AJ, 112, 545
Pryor, C., & Meylan, G. 1993, in The Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski & G. Meylan (San Francisco: ASP), 357
Shawl, S. J., & White, R. E. 1986, AJ, 91, 312
Shara, M. M., Moffat, A. F. J., Potter, M., Hogg, H. S., & Wehlau, A. 1986, ApJ, 311, 796
Smith, G. H., & Norris, J. 1982, ApJ, 254, 149
Smith, G. H., & Wing, R. F. 1973, PASP, 85, 659
Smith-Kogan, C., Wehlau, A., & Demers, S. 1974, AJ, 79, 387
Stetson, P. B., Davis, L. E., & Crabtree, D. R. 1990, in ASP Conf. Proc. 25, CCDs in Astronomy, ed. G. H. Jacoby (San Francisco: ASP), 297
Trager, S., King, I. R., & Djorgovski, S. G. 1995, AJ, 109, 218
van der Marel, P. A., & Dolphin, A. E. 2001, PASP, 104, 888
Webbink, R. F. 1981, ApJS, 45, 259
Wehlau, A., & Froebrich, N. 1994, AJ, 108, 134
Zinn, R. 1981, ApJ, 251, 52

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Fig. 1.—$B$ image of M14 taken with MOS on the CFHT. The carbon star is identified by the small circle, while the larger circle denotes the cluster core radius ($r_c = 50''$ according to Trager, King, & Djorgovski 1995). The cross shows the location of the cluster center (Shaw & White 1986). North is up, and east is to the left on this image, which measures $3''75 \times 3''5$.  

Côrê et al. (see 476, L16)