Mengle, J. G., Sweigart, A. V., Demarque, P., and Gross, P. G. 1979, ApJS, 40, 733
Nemec, J. M. 1989, The Use of Pulsating Stars in Fundamental Programs in Astronomy, ed. E. D. Schmidt (Cambridge, Cambridge University Press), p. 215
Nemec, J. M., and Mateo, M. 1990, in The Evolution of the Universe of Galaxies, ASP Conf. Ser. 10, ed. R. G. Kron, p. 134
Nemec, J. M., Nemec, A. F. L., and Lutz, T. E. 1994, AJ, 108, 322
Nemec, J. M. 1995, ASP Conf. Ser 83, ed. R. S. Stobie and P. A. Whitelock, p. 207
Powell, J. M., Joner, M. D., and McNamara, D. H. 1990, PASP, 102, 1131
Przybyski, A., and Bessell, M. S. 1979, MNRAS, 189, 377
Reid, I. N., and Freedman, W. 1994, MNRAS, 267, 821
Rodriguez, E., Rolland, A., and López de Coca, P. 1988, RMxAA, 16, 7
Rodriguez, E., Rolland, A., and López de Coca, P. 1990b, Ap&SS, 169, 113
Rodriguez, E., López de Coca, P., Rolland, A., and Garrido, R. 1990a, RMxAA, 20, 37
Rodriguez, E., Rolland, A., López de Coca, P., Garcia-Lobo, E., and Sealano, J. L. 1992, A&AS, 93, 189
Rodriguez, E., Rolland, A., and López de Coca, P. 1993, A&AS, 101, 421
Rodriguez, E., Rolland, A., Costa, V., and Martin, S. 1995, MNRAS, 227, 965
Rolland, A., Rodriguez, E., López de Coca, P., and Garcia-Palayo, J. M. 1991, A&AS, 91, 374
Sandage, A. 1993, AJ, 106, 703
Smith, H. J. 1955, unpublished dissertation, Harvard University
Sonneborn, G., Fransson, C., Lundquist, P., Cassatella, A., Gilmozzi, R., Kirshner, R. P., Panagia, N., and Wamsteker, W. 1996, preprint
Vandenberg, D. A. 1985, ApJS, 58, 711
van Leeuwen, F., Feast, M. W., Whitelock, P. A., and Yudin, B. 1997, MNRAS, 287, 955
Walker, A. R. 1992, ApJ, 390, L81
Walker, A. R. 1994, AJ, 108, 555
Walker, A. R. 1997, ApJ, 390, L81
Woltjer, L. 1956, Bull. Astron. Inst. Netherlands, 13, 53
Young, K. A. 1976, Thesis, Brigham Young University
M Subdwarf Secondaries: A Test of the Metallicity Scale

JOHN E. GIZIS AND I. NEILL REID

Palomar Observatory, 105-24, California Institute of Technology, Pasadena, California 91125
Electronic mail: jeg@astro.caltech.edu, inr@astro.caltech.edu
Received 1997 June 9; accepted 1997 August 26

ABSTRACT. We present spectra of three M subdwarfs which are common-proper-motion companions to F or G subdwarfs of known metallicity. The assumption that the companions have the same composition allows us to test the Gizis (1997, AJ, 113, 806) M subdwarf classification system and its correspondence to metallicity. The results are in excellent agreement with the Gizis (1997, AJ, 113, 806) scale, thereby showing that the Allard and Hauschildt (1995, ApJ, 445, 433) extended model atmospheres agree well in the 6200–7400 Å region for cool metal-poor stars. We also show that the results are consistent with the main sequences of globular clusters using the Reid (1997a, AJ, in press) distance scale.

1. INTRODUCTION

The metal-poor stars of the thick disk and halo provide an invaluable record of Galactic history. The main-sequence FGK subdwarfs have proven to be an important source of information on these populations (e.g., Carney et al. 1994). The much cooler and fainter M subdwarfs offer an important alternative tracer group. Indeed, in addition to the possibility of observing nearby proper-motion M subdwarfs, it is now feasible to obtain both photometry for the M subdwarfs in globular clusters with the Hubble Space Telescope (e.g., Santiago et al. 1996) and spectra for M dwarfs and M subdwarfs at distances of a few kiloparsecs above the galactic plane with 10-m class telescopes (Reid et al. 1997). Using these objects as probes of Galactic structure, however, requires a good understanding of their properties in order to derive metallicities and luminosities.

Gizis (1997, hereafter G97) has presented a spectroscopic classification scheme which is based on moderate resolution (~3 Å) spectra covering the wavelength range 6200–7400 Å. Quantitative bandstrength indices measuring TiO and CaH features are used to classify stars as M V (ordinary disk stars), sdM (M subdwarfs), and esdM (extreme M subdwarfs). Comparison to the Allard and Hauschildt (1995) synthetic spectra allowed G97 to show that these classes correspond to [m/H]~0.0, [m/H]~−1.2±0.3, and [m/H]~−2.0±0.5, respectively. Comparison of the (M_V,V−I) HR diagram shows that HST globular-cluster sequences (Santiago et al. 1996) and stellar interior calculations with Allard and Hauschildt (1995) model atmospheres (Baraffe et al. 1995) are in agreement with this scale; however, serious systematic errors could in principle affect all of these methods of estimating metallicity.

We present spectra of three M subdwarfs which are companions to hotter subdwarfs of known metallicity. Our aim is to test the metallicities derived from the M subdwarf spectra by comparison with those measured for their better understood primaries. The data are presented in Sec. 2, the implications for the metallicity scale are discussed in Sec. 3, and the results are summarized in Sec. 4.

2. OBSERVATIONS

We observed two systems (G 116-009; G 176-046) whose low-luminosity components were recently discovered (Martin and Rebolo 1992; Martin et al. 1995). We also observed VB 12 (LHS 541), the low-luminosity companion to HD 219617 (LHS 540) discovered by van Briesbroeck (1961). All three stars were identified as common proper-motion companions to already-known, relatively bright, high proper-motion objects. We refer to the low-luminosity component of G 116-009 as G 116-009B and the primary as G 116-009A. CLLA find that G 116-009A has B−V=0.86, corresponding to T_eff=4750 K. The case of the G 176-046 system is rather complicated—Martin et al. (1995) note that their object is the fourth member of this system, since Latham et al. (1992) deduce that G 176-046 is a spatially unresolved triple from their high-resolution spectra. We therefore will refer to the low-luminosity companion as G 176-046D and the primary as G 176-046ABC. Latham et al. (1992) find that this “primary” has B−V=0.80 and T_eff=4860 K. In fact, this system is a quintuple system, since Ryan (1992) has shown that LP 215-35 is a common proper-motion companion at 343" separation. This companion has B−V=0.86. VB 12’s primary, HD 219617, is itself a double star with an orbital semi-major axis of 0.80 (Heintz 1991). CLLA find B−V =0.48 and T_eff =5857 K.

The stars were observed with the Palomar 200 in. on UT Date 1997 June 1 using the Double Spectrograph. A dichroic which divided the light at 5500 Å was used. The red camera was used with a 600 l/mm grating, yielding wavelength coverage from 6040 to 7380 Å at ~3 Å resolution. Very few counts were obtained in the blue camera for the M subdwarfs and those data were therefore not used. The setup is similar to that used by Reid et al. (1995) and G97. The spectra were wavelength calibrated with neon and argon lamps and flux calibrated with the Gunn and Oke (1983) standards using FIGARO.

The resulting spectra are plotted in Fig. 1. We measure bandstrength indices defined in Table 1 as the ratio of flux in the features (W) to flux in the pseudo-continuum regions (S1 and S2). They were originally defined in Reid et al. (1995).
Fig. 1—Spectra of the three metal-poor M subdwarf companions. The spectra have been renormalized by a mean value of 1. G116-009B and VB 12, respectively, have been displaced upwards by 2 and 4, respectively.

Our measurements of the indices as well as photometry from the literature are reported in Table 2. Standards from Marcy and Benitz (1989) were used as templates to determine radial velocities accurate to ±20 km s\(^{-1}\) for the M subdwarfs. All are consistent with the more precisely known primary velocities. The metallicities derived by Carney et al. (1994, hereafter CLLA) for the primaries are also listed in Table 2.

### Table 1: Spectroscopic Indices

| Band   | SI | W | S2 |
|--------|----|---|----|
| TiO 5  | 7042–7046 | 7126–7135 |
| CaH 1  | 6345–6355 | 6380–6390 | 6410–6420 |
| CaH 2  | 7042–7046 | 6814–6846 |
| CaH 3  | 7042–7046 | 6960–6990 |

3. THE METALLICITY SCALE

G97 found that the mean \([m/H]\) for the sdM and esdM are \(-1.2\), with a range of ±0.3, and \(-2.0\), with a range of ±0.5, respectively. G97 also argued that stars of \([m/H] \geq -0.6\) are not distinguishable on the basis of their indices from ordinary (near solar metallicity) nearby M dwarfs. The three stars in the present sample have classifications of M1.0 V, sdM0.5, and sdM3.0. We can derive more quantitative metallicity estimates by considering the values of band-strength indices rather than the shorthand classification. The three stars are compared to the G97 standards in the TiO-CaH diagrams in Fig. 2. The two sdM stars G 116-009B and VB 12 lie quite close to the separation line between sdM and esdM, implying that they have similar \([m/H]\) near to the lower end of the sdM range, i.e., \(-1.4 \text{ or } -1.5\). The indices of G 176-046D indicate that it is substantially more metal rich than the other stars. Although classified as \textquoteleft\textquoteleft M1.0 V,\textquoteright\textquoteright G 176-046D lies within 0.01 in CaH1 of being classified as \textquoteleft\textquoteleft sdM,\textquoteright\textquoteright This offset is less than the observational error of ±0.02. We conclude that this subdwarf lies at the upper range of sdM abundances and at the lower extreme of the high-velocity disk (Intermediate Population II) stars, so \(-0.6 < [m/H] < -0.9\).

These expectations from the analysis of the M subdwarf spectra are confirmed by the CLLA measurements of the primaries. G 116-009A has \([m/H] = -1.46\). This system provides the cleanest test, since CLLA's finding of no radial velocity variations implies the primary is single. HD 219617 has \([m/H] = -1.40\) but is an unresolved binary. It should be noted that Axer et al. (1994) derive a significantly higher value of \([Fe/H] = -1.08\), but specifically note that their value is \textquoteleft\textquoteleft suspect.	extquoteright\textquoteright The CLLA values are in good agreement with our M subdwarf estimates for both stars above. Finally, we must consider G 176-046. CLLA derive \([m/H] = -1.07\) but since the \textquoteleft\textquoteleft primary\textquoteright\textquoteright is made up of three stars this value is uncertain. An independent estimate may be obtained from the Ryan (1992) \(UBV\) photometry of the distant subdwarf companion LP 215-35. Inspection of Ryan's Fig. 1 shows that LP 215-35 is more metal-rich than \([m/H] < -1\). His photometry of G 176-046ABC implies \([m/H] = -1\), but this may also be affected by its unresolved nature. The M subdwarf calibration, indicating that the system is probably slightly more metal-rich than \(-1\), is more consistent with the LP 215-35 photometry than with the G 176-046ABC data. In any case, we can at least conclude that \([m/H] = -1.07\) measurement is consistent with the position of G 176-046D above the \([m/H] = -1.2\) sdM but below the \([m/H] = -0.6\) stars.

The spectroscopic classification can be tested against position in the HR diagram for VB 12.\(^2\) HD 219617 has a \textit{Hipparcos} trigonometric parallax \((\pi = 12.41 \pm 2.04 \text{ milliarcsec})\). VB 12 has \(V = 16.46\), \(V-I = 2.09\), (Bessell 1990) implying \(M_V = 11.93\). These values place it slightly above the extreme subdwarf sequence (Monet et al. 1992; Gizis 1997) as expected from the bandstrength indices.

The current G97 M-subdwarf metallicity scale is in good agreement with the CLLA metallicities although the possibility remains of systematic uncertainties at the ±0.3 dex level. One potential problem is the elemental abundance ratios used in the Allard and Hauschildt (1995) model atmospheres which form the basis of the G97 calibration. Those atmospheres are computed using scaled solar metallicities. However, Ruan's (1991) spectroscopic analysis of VB 12( and HD 219617) indicates that both stars have the ex

\(^3\)The metallicities for G 116-009A and G 176-046ABC cited in Martin et al. (1995) are those derived by Laird et al. (1988) which are significantly more metal-poor than the more recent estimates given by CLLA. As a result, the comparison of G176-046 and G116-009 to \(\omega\) Cen made by Martin et al. is no longer appropriate.

\(^2\)Neither of the other systems has a reliable trigonometric parallax measurement.
expected oxygen and $\alpha$ enhancement, and that changing the abundance ratios has a significant effect on the colors. Baraffe et al. (1997) have argued that the appropriate method of comparing stellar interior models (as well as stellar atmosphere models) for the M subdwarfs is to consider $[\text{m/H}]=[\text{O/H}]+[\text{O/Fe}][\text{Fe/H}]+0.35$ for $[\text{Fe/H}] \leq -1$. They find that the Monet et al. (1992) esdM are consistent with an average $[\text{m/H}]$ of $-1.3$ or $-1.5$ based upon the $(M_V, V-I)$ HR diagram, whereas G97 found $[\text{m/H}] = -2 \pm 0.5$ for the same stars on the basis of spectroscopy. The discrepancy between the two calibrations is thus at least 0.5 dex.

Since the publication of Gizis’ analysis, Reid (1997a) and Gratton et al. (1997) have used main-sequence fitting to rederive distances to a number of well-known clusters, using nearby F and G subdwarfs with high-precision Hipparcos parallax measurements as local calibrators. The resultant distances are significantly higher for the lowest abundance clusters (such as M92, M15, and NGC 6397). We can compare the recalibrated cluster color-magnitude diagrams against the $(M_V, V-I)$ distribution of the local M subdwarfs. In Fig. 3, we plot the parallax subdwarfs classified by Gizis (1997). We readjust published globular-cluster main sequences to the distances and reddenings used by Reid (1997a, 1997b). We use the clusters NGC 6397 (Cool et al. 1996); M15 (Santiago et al. 1996); and 47 Tuc (Santiago et al. 1996). The metallicities $[\text{Fe/H}]$ for these clusters are $-1.82$, $-2.12$, and $-0.70$, respectively (Carretta and Gratton 1997). NGC 6397’s main sequence passes through the esdM sequence. M15 lies at the bottom edge of esdM distribution, although the HST data do not extend very far to the red. As in G97, 47 Tuc lies above the sdM, indicating that they have $[\text{m/H}] < -0.7$. Thus, an empirical calibration suggests that the G97

| Star      | $V$ | $V-I_C$ | Source | Sep. ($\arcsec$) | Ti05 | CaH1 | CaH2 | CaH3 | Sp. Type | [m/H] |
|-----------|-----|---------|--------|------------------|------|------|------|------|----------|-------|
| G 116-009B | 18.4 | 2.0     | MR     | 10.2             | 0.93 | 0.83 | 0.65 | 0.84 | sdM0.5   | -1.46 |
| G 176-046D | 18.0 | 2.2     | MR     | 4.7              | 0.76 | 0.80 | 0.63 | 0.83 | M 1.0 V  | -1.07 |
| VB 12      | 16.46| 2.09    | B      | 15               | 0.71 | 0.60 | 0.44 | 0.65 | sdM3.0   | -1.40 |

*Photometry sources are MR (Martin and Rebolo 1992; Martin et al. 1995) and B (Bessell 1990).
M subdwarf abundance scale is consistent with the globular cluster \([\text{Fe}/\text{H}]\) scale.

4. SUMMARY

We have compared the metallicities estimated directly from spectra of three M subdwarfs to the metallicities derived for their FGK subdwarf companions. We find that the metallicities based on the Gizis (1997) spectroscopic classification system are consistent with the metallicities derived by Carney et al. (1994) from high-resolution spectra. We argue that \([m/\text{H}]\) on the G97 scale corresponds to \([m/\text{H}] - [\text{Fe}/\text{H}]\).

We thank the Palomar Observatory staff for their capable support. J.E.G. gratefully acknowledges support by Greenstein and Kingsley Fellowships as well as NASA Grants GO-06344.01-95A and GO-05913.01-94A. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Allard, F., and Hauschildt, P. H. 1995, ApJ, 445, 433
Axer, M., Fuhrmann, K., and Gehren, T. 1994, A&A, 291, 895
Bessell, M. S. 1990, A&AS, 83, 357
Baraffe, I., Chabrier, G., Allard, F., and Hauschildt, P. H. 1995, ApJ, 446, L35
Baraffe, I., Chabrier, G., Allard, F., and Hauschildt, P. H. 1997, A&A, in press
Carney, B. W., Latham, D. W., Laird, J. B., and Aguilar, L. A. 1994, AJ, 107, 2240 (CLLA)
Carretta, E., and Gratton, R. G. 1997, A&AS, 121, 95
Cool, A. M., Piotto, G., and King, I. R. 1996, ApJ, 468, 655
Gizis, J. E. 1997, AJ, 113, 806 (G97)
Gratton, R. G., Fusi Pecci, F., Carretta, E., Clementini, G., Corsi, C. E., and Lattanzi, M. 1997, ApJ, in press
Gunn, J. E., and Oke, J. B. 1983, ApJ, 266, 723
Heintz, W. D. 1991, A&AS, 90, 311
Laird, J. B., Carney, B. W., and Latham, D. W. 1988, AJ, 95, 1843
Latham, D. W., Mazeh, T., Stefanik, R. P., Davis, R. J., Carney, B. W., Krymolowski, Y., Laird, J. B., Torres, G., and Morse, J. A. 1992, AJ, 104, 774
Marcy, G. W., and Benitz, K. J. 1989, ApJ, 344, 441
Martin, E. L., and Rebolo, R. 1992, Complementary Approaches to Double and Multiple Star Research, IAU Colloquium 135, ed. H. A. McAlister and W. I. Hapiktopf, ASP Conf. Ser., Vol. 32, p. 336
Martin, E. L., Rebolo, R., and Zapatero Osorio, M. R. 1995, The Bottom of the Main Sequence—and Beyond, ed. C.G. Tinney (Springer, Berlin), p. 253
Monet, D. G., Dahn, C. C., Vrba, F. J., Harris, H. C., Pier, J. R., Luginbuhl, C. B., and Ables, H. D. 1992, AJ, 103, 638
Reid, I. N. 1997a, AJ, 114, 161
Reid, I. N. 1997b, AJ, in press
Reid, I. N., Gizis, J. E., Cohen, J., Phare, M., Hogg, D., Cowie, L., Hu, E., and Songaila, A. 1997, PASP, 109, 559
Reid, I. N., Hawley, S. L., and Gizis, J. E. 1995, AJ, 110, 1838
Ruan, K. 1991, Ph.D. thesis, The Australian National Observatory
Ryan, S. G. 1992, AJ, 104, 1144
Santiago, B. X., Elson, R. A. W., and Gilmore, G. F. 1996, MNRAS 281, 1363
van Briesbroeck, G. 1961, AJ, 66, 528