HIGH CHROMOSPHERIC ACTIVITY IN M SUBDWARFS

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ABSTRACT

We present spectroscopic observations of two halo M subdwarfs that have Hz emission lines. We show that in both cases close companions are the likely cause of the chromospheric activity in these old, metal-poor stars. We argue that Gl 781A's unseen companion is most likely a cool helium white dwarf. Gl 455 is a near-equal-mass M subdwarf (sdM) system. Gl 781A is rapidly rotating, with $v \sin i \approx 30 \text{ km s}^{-1}$. The properties of the chromospheres and X-ray coronae of these systems are compared with M dwarfs with emission (dMe's). The X-ray hardness ratios and optical chromospheric line emission ratios are consistent with those seen in dMe stars. Comparison with active near-solar metallicity stars indicates that, despite their low metallicity ([M/H] $\approx -1.2$), the sdMe stars are roughly as active in both X-rays and chromospheric emission. Measured by $L_{\text{bol}}/L_{\text{bol}}$, the activity level of Gl 781A is no more than a factor of 2.5 subluminous with respect to near-solar-metallicity stars.

Key words: binaries: spectroscopic — stars: activity — stars: late-type — stars: Population II

1. INTRODUCTION

It has long been noted that most old halo stars show little magnetic activity relative to young disk stars—indeed, Joy (1947) used "a weakening of emission lines" as one of the criteria for identifying M subdwarfs. For disk stars, magnetic activity has been extensively studied from the onset of the convective envelope among F stars down to the hydrostatic activity has been extensively studied from the onset of the convective envelope among F stars down to the hydrogen burning limit (as reviewed by Haisch & Schmitt 1996). Comparatively little is known about the activity of Population II stars: recent studies of them have addressed the classification of metal-poor stars as sdM (Gizis 1997) and X-ray emission in binary systems (Ottmann, Fleming, & Pasquini 1997), but these studies targeted near-solar-mass stars rather than very low mass stars. Nevertheless, the Population II M subdwarfs are worthy of study, because stars with $M \leq 0.35 M_\odot$ are thought to be fully convective for all metallicities (Chabrier & Baraffe 1997) and, therefore, may have a different dynamo mechanism than solar-mass stars that have radiative/convective zone boundaries (Giammapa et al. 1996; Durney, De Young, & Roxburgh 1993).

Moderate-resolution spectra of very low mass stars allow the identification of high-activity ("dMe") stars by the presence of Hz emission lines while at the same time allowing the classification (Gizis 1997) of metal-poor stars as sdM (M subdwarfs) and esdM (extreme M subdwarfs). In our recent Palomar/Michigan State University (PMSU) Nearby-Star Spectroscopic Survey (Reid, Hawley, & Gizis 1995a; Hawley, Gizis, & Reid 1996), two of 2063 stars showed both Hz emission and anomalously weak TiO bands, indicating that these stars are sdMe's. The PMSU sample consisted of the known main-sequence M stars within 25 pc and therefore was largely made up of disk stars with metallicity near solar. Subsequently, Gizis (1997) surveyed a sample of cool high-velocity stars, identifying an additional 27 sdM's and 17 esdM's. Including our recent spectra of previously unobserved faint high proper motion stars (Gizis & Reid 1997a; Gizis & Reid 1997b), we have observed a total of 68 sdM and esdM stars. Only the original two subdwarfs show emission. Gizis (1997) classified Gl 781 (LHS 482) as sdM1.5e and Gl 455 (LHS 2497) as sdM3.5e. By fitting the synthetic spectra of Allard & Hauschildt (1995), Gizis (1997) showed that the sdM stars have [M/H] $\approx -1.2 \pm 0.3$.

We present additional observations of these two sdMe systems aimed at understanding their nature and investigating the characteristics of their activity. Both stars prove to be close binary systems. We present the data in § 2, discuss both the unusual Gl 781 system and the magnetic activity levels in § 3, and summarize our conclusions in § 4.

2. DATA ANALYSIS

Spectra were obtained using the echelle spectrograph (McCarthy 1985) of the Palomar 60 inch (1.5 m) telescope. The red cross-dispersing prisms were used, yielding wavelength coverage from 4700 to 9200 Å with gaps between orders beyond 7000 Å. The 2 pixel resolution was 0.3 Å. Gl 455 was observed on 1995 December 31, 1996 January 4, and twice on 1996 January 6. Gl 781 was observed 23 times on UT dates 1996 August 8 and 9; four other observations were taken in 1994 July.

The echelle data were reduced on a SPARC 5 running UNIX using the ECHELLE FIGARO routines (Tomaney & McCarthy 1998). Radial velocities were found by cross-correlation with the M dwarf standards from Marcy & Benitz (1989). Comparison of other M dwarfs observed on the same observing runs with high-precision radial velocities show that the accuracy is $\pm 2 \text{ km s}^{-1}$; these uncertainties will be discussed in more detail in Gizis, Reid, & Hawley (1998). The radial velocities are given in Tables 1 and 2.

No lines from a companion were seen in the spectrum of Gl 781 (Fig. 1), which shows large velocity variations (Joy 1947); however, our monitoring yields a reliable period estimate. T. Mazeh and D. Goldberg kindly calculated orbital solutions using both 1995 June and 1996 August data. Because of the large separation in time between the observations, there are a number of different possible periods.
TABLE 1

VELOCITY DATA FOR GI 781

| JD          | $V_{\text{rad}}$ (km s$^{-1}$) | JD          | $V_{\text{rad}}$ (km s$^{-1}$) | JD          | $V_{\text{rad}}$ (km s$^{-1}$) |
|-------------|-------------------------------|-------------|-------------------------------|-------------|-------------------------------|
| 2,449,559.78284... | 70.59                       | 2,450,303.773024... | 77.66                       | 2,450,304.757906... | 75.85                       |
| 2,449,560.793864... | 80.78                       | 2,450,303.821616... | 84.31                       | 2,450,304.801232... | 87.79                       |
| 2,449,561.789240... | 57.89                       | 2,450,303.881348... | 32.56                       | 2,450,304.807671... | 86.17                       |
| 2,449,561.856991... | −37.40                      | 2,450,303.932413... | −42.01                      | 2,450,304.811984... | 85.73                       |
| 2,450,303.661066... | −61.09                      | 2,450,304.930908... | −102.64                     | 2,450,304.816111... | 82.87                       |
| 2,450,303.685817... | −23.23                      | 2,450,304.002925... | −134.41                     | 2,450,304.827800... | 34.81                       |
| 2,450,303.821029... | 16.40                       | 2,450,304.022841... | −150.44                     | 2,450,304.925684... | −39.83                      |
| 2,450,303.932413... | 22.64                       | 2,450,304.661833... | −47.03                      | 2,450,304.971999... | −111.42                     |
| 2,450,303.973081... | −37.40                      | 2,450,304.975199... | −152.47                     | 2,450,304.975199... | −111.42                     |
| 2,450,304.801232... | 16.40                       | 2,450,304.975199... | −152.47                     | 2,450,304.975199... | −111.42                     |

Orbital solutions for each period are given in Table 3. Note that all periods lie within the range $0.497 \pm 0.001$ days. We will refer to the observed, brighter sdM star as Gl 781A and the unseen, fainter companion as Gl 781B. The mass of Gl 781A is likely to be $<0.25 M_\odot$, according to the models of D’Antona & Mazzitelli (1996) and Baraffe et al. (1995).

TABLE 2

VELOCITY DATA FOR Gl 455

| JD          | $v_A$ (km s$^{-1}$) | $v_B$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | COMMENT |
|-------------|---------------------|---------------------|--------------------------|---------|
| 2,450,083.05575... | 52.9               | −1.6               | 54.5                     | Resolved |
| 2,450,087.002654... | −1.1               | 57.7               | 58.7                     | Resolved* |
| 2,450,088.909443... | 29.2               | ...                | <15                      | Unresolved |
| 2,450,088.996125... | 30.1               | ...                | <15                      | Unresolved |

* The spectra of the two components are sufficiently similar that the identification of "A" and "B" may be incorrect.

With the observed mass function, $M \sin i = 0.3 M_\odot$ for Gl 781B.

The absorption lines in Gl 781A are broadened compared with other M dwarfs observed with the same setup. To measure this broadening, we artificially broadened spectra of nonrotating stars obtained on the same night by convolving with the rotation profile (Gray 1992). We used the M1.5 V star Gl 880 as the standard. Marcy & Chen (1992) determined the upper limit on this star’s rotational velocity to be $1.1 \pm 1.1$ km s$^{-1}$. The least-squares fit of the atomic lines yields $v \sin i = 30 \pm 5$ km s$^{-1}$. To rule out the possibility of metallicity differences causing the broadening, we have repeated this procedure using the inactive sdM1.5 star LHS 64. LHS 64 does not show measurable broadening relative to Gl 880, and fitting the Gl 781 spectra to artificially broadened LHS 64 spectra again yields $v \sin i = 30$ km s$^{-1}$. We note, however, that Stauffer & Hartmann (1986) measured $v \sin i = 15$ km s$^{-1}$ for Gl 781A. Stauffer & Hartmann also measured $v \sin i = 15$ km s$^{-1}$ for Gl 82 and

![Fig. 1.—Spectra of the sdM1.5 stars Gl 781 and LHS 64. LHS 64 has been shifted by 338 km s$^{-1}$ to match Gl 781A at this epoch. Note the broadening of Gl 781A’s absorption lines with respect to LHS 64’s. No lines from a companion to Gl 781A are evident.](image-url)
GL 268. We also have spectra of these stars using the same spectrograph setup—Gl 781A’s absorption lines are clearly broader. We therefore prefer our own measurement.

The Hα and Hβ emission lines show significant variability. The Hα line varies between 1.0 and 1.3 Å in the 1996 August spectra, with no dependence on orbital phase. In the 1994 July spectra, Hα is seen between 1.3 and 1.6 Å. Previous low-resolution observations (Reid et al. 1995a) observed Hα in a stronger state (1.9 Å). The Hβ region is observed at a low signal-to-noise ratio, but Hβ is definitely also variable, with equivalent width of 1.7 Å when EW_{Hα} = 1.3 Å. Based on low-resolution spectrophotometry, obtained with the Palomar 60 inch telescope and spectrograph in 1996 July, we estimate the continuum flux level as 1.1 × 10^{-13} ergs cm^{-2} s^{-1} Å^{-1} at Hα and 4.7 × 10^{-14} ergs cm^{-2} s^{-1} Å^{-1} at Hβ. These indicate a line flux between 1.1 × 10^{-13} and 2.1 × 10^{-13} ergs cm^{-2} s^{-1} for Hα, and a Balmer decrement of 1.8 for the EW_{Hα} = 1.3 Å observation. The He D3 line was detected with observed equivalent width of 0.15 ± 0.5 Å. The He triplet at 6678Å was also marginally detected with an equivalent width of ~0.1 Å (this line is difficult to measure, as it lies near a TiO band head).

Our four echelle spectra of Gl 455 clearly indicate that it is a double-lined spectroscopic binary but do not provide enough data to determine the orbital parameters. In the first two spectra (1995 December 31 and 1996 January 4), the absorption lines from both components are resolved, with the cores separated but the wings overlapping. The other two spectra (1996 January 6) do not show line doubling. The small shift (0.9 km s^{-1}) seen for the observations separated by 2 hr suggests the period is much longer than Gl 781’s period. We note that the velocity data are consistent with an ~8 or ~16 day period. It should also be noted that since the lines are never completely separated we cannot rule out the possibility that there is a (fainter) third star in this system; Gizis (1997) showed that the two components of Gl 455 appear to lie above the sdM sequence in the H-R diagram even after correcting for binarity. We do not detect rotational broadening in this system, indicating that v sin i ≤ 15 km s^{-1}. Since our resolution is insufficient to detect rotational broadening in most dMe’s (Gizis et al. 1998), this limit on the rotation is not surprising. If the period is 8 days, then we estimate that the equatorial rotational velocities are ~1.3 km s^{-1}.

The Hζ emission of Gl 455AB is not resolved, so the reported equivalent widths are for the combined spectrum. In the 1995 December spectrum, the Hβ line is resolved sufficiently to show that both components are in emission. Significant variability is present: the four equivalent widths of Hα are 0.9, 1.1, 0.3, and 0.6 Å and those of Hβ are 2.0, 1.6, 0.3, and 0.7 Å. Our earlier moderate-resolution spectrum (Hawley et al. 1996) had an Hβ equivalent width of less than 1 Å. We therefore adopt the Hβ equivalent width of 0.6 Å as a “typical” value for the discussion of this system’s activity level. Our 1996 July spectrophotometry indicates that the continuum flux near Hα for the two unresolved components is approximately 5 × 10^{-14} ergs cm^{-2} s^{-1} Å^{-1}. We therefore estimate the “typical” Hα flux to be 1.5 × 10^{-14} ergs cm^{-2} s^{-1} for each star, under the assumption of equal-luminosity components.

We have searched the ROSAT All-Sky Survey (Voges et al. 1998) to determine whether the sdMe are X-ray sources. We identify Gl 781 with 1RXS J200503.8+542609 and Gl 455 with 1RXS J120219.1+283507. The hardness ratio (HR1) given in the catalog is nearly identical to the hardness

| Solution | P (days) | γ | K | e | ω (deg) | T_{p0} (JD) | f(m) |
|----------|---------|---|---|---|---------|------------|------|
| A        | 0.49603807 | -33.97 | 123.31 | 0.0136 | 212 | 2,450,193.974 | 0.0965 |
| B        | 0.49636949 | -34.06 | 123.31 | 0.0123 | 212 | 2,450,194.397 | 0.0966 |
| C        | 0.49670134 | -34.15 | 123.29 | 0.0109 | 212 | 2,450,194.323 | 0.0966 |
| D        | 0.49703363 | -34.23 | 123.27 | 0.0095 | 211 | 2,450,194.249 | 0.0966 |
| E        | 0.49736636 | -34.31 | 123.24 | 0.0081 | 210 | 2,450,194.174 | 0.0966 |
| F        | 0.49769953 | -34.38 | 123.20 | 0.0066 | 208 | 2,450,194.097 | 0.0966 |
| G        | 0.49803314 | -34.45 | 123.16 | 0.0051 | 204 | 2,450,194.018 | 0.0966 |
| σ        | 0.00000002 | 0.58 | 0.91 | 0.0061 | 70 | 0.097 | 0.0221 |

TABLE 4

Stellar Parameters

| Data | Gl 781A | Gl 455AB |
|------|---------|----------|
| V    | 11.98   | 12.85^a |
| V−Ic | 1.99    | 2.47^a  |
| d (pc)| 16.6    | 20.3    |
| M_{bol} | 10.88 | 12.06^b |
| M_{bol} | 9.58  | 10.50^b |
| Luminosity (10^{35} ergs s^{-1}) | 4.6  | 2.0^b  |
| T_{eff} (K) | 3600 | 3500^b |
| Radius (R_{Sun}) | 0.28 | 0.20^b |
| Mass (M_{Sun}) | 0.25 | 0.15^b |
| HR1   | -0.41  | -0.74^a |
| f_k (10^{-13} ergs cm^{-2} s^{-1}) | 6.60 | 3.91^a |
| L_k (10^{35} ergs s^{-1}) | 22  | 9.7^a |
| <EW(Hα)> | 1.3 | 0.6^a |
| log (L_{bol}/L_{bol}) | -0.6 | -1.1 |
| log (L_{bol}/L_{bol}) | -3.9 | -4.4 |
| log (L_{bol}/L_{bol}) | -3.3 | -3.3 |
| v sin i (km s^{-1}) | 30  | ≤ 15 |
| P_{orb} (days) | 0.5 | ? |

^a Value for unresolved system.

^b Value for individual star A or B, assuming equal-luminosity components.

^c Estimated from stellar models.

^d "Typical" value used to estimate activity levels involving L_{bol}.

TABLE 3

Orbital Solutions for Gl 781

| No. 5, 1998 | CHROMOSPHERIC ACTIVITY | 2055 |

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We have searched the ROSAT All-Sky Survey (Voges et al. 1998) to determine whether the sdMe are X-ray sources. We identify Gl 781 with 1RXS J200503.8+542609 and Gl 455 with 1RXS J120219.1+283507. The hardness ratio (HR1) given in the catalog is nearly identical to the hardness
ratio (HR) used by Schmitt, Fleming, & Giampapa (1995) to study nearby dM and dMe stars. We therefore determine the count rate–energy conversion factor (CF) using their equation:

\[ CF = (5.30 \times 10^{-12}) \times \text{ergs cm}^{-2} \text{ s}^{-1} \text{ counts}^{-1}. \]

The derived X-ray fluxes and other stellar parameters used in this paper are given in Table 4.

3. DISCUSSION

3.1. Binary Gl 781 and Its History

The observed mass function of the system and the theoretically estimated mass of Gl 781A imply that Gl 781B is probably more massive \((M_B \sin i \approx 0.3 \, M_\odot)\). Together with the fact that no lines are seen, this mass implies that Gl 781B is a faint, cool white dwarf. The line strengths, colors, and absolute magnitude of Gl 781A are similar to other sdM's, so we estimate that the white dwarf is \(\geq 2 \, \text{mag} \) fainter, i.e., \(M_V \geq 13\). Ordinary white dwarfs \((M \approx 0.6 \, M_\odot)\) have ages \(\geq 10^8\) yr at this luminosity (D'Antona & Mazzitelli 1990; we have used the Liebert, Dahm, & Monet 1988 bolometric corrections). As shown below, the most likely possibility is that Gl 781B is a \(\approx 0.35 \, M_\odot\) helium white dwarf—the corresponding lower limit on the age is \(2 \times 10^9\) yr (Hansen & Phinney 1998).

The detection of rotational broadening serves as a constraint on the possible system parameters. Assuming that Gl 781A's rotational period is the same as that of the system,

\[ \sin i = \frac{P_{\text{rot}}}{2\pi R_{\text{GIZIS}}} \]

The radius of the star is not known but can be estimated, either from stellar interior models or by using the bolometric corrections and effective temperatures from model atmospheres (Allard & Hauschildt 1995) as fitted by GIZIS (1997). Using the latter method, we estimate \(L \approx 4.6 \times 10^{31}\) \text{ergs s}^{-1} \text{ and } \text{Teff} \approx 3600 \text{ K}, so \(R \approx 0.28 \, R_\odot\). This estimate is in good agreement with stellar interior models (Baraffe et al. 1997). We then find that we expect \(v_{\text{rot}}\) to be \(29 \pm 6 \text{ km s}^{-1}\), compared with the observed \(v_{\text{rot}} \sin i \approx 30 \pm 5 \text{ km s}^{-1}\), suggesting the system is viewed nearly edge-on, with \(i \approx 1\). If \(i \approx \text{indeed near unity, then the white dwarf companion has an unusually small mass. Gravitational redshift measurements show that the distribution of white dwarf masses in wide binaries is strongly peaked at } M = 0.59 \, M_\odot \text{ (Reid 1996). This peak mass cannot be reconciled with the radius of Gl 781A deduced from the observed luminosity and effective temperature. Thus, the observations require that Gl 781B be about half the mass of the typical relatively isolated white dwarf.}

The small present-day separation of the two stars, \(a \approx 7 \, R_\odot\), implies that Gl 781A was engulfed when Gl 781B became a red giant (recall that the present-day brighter component, the sdM, was then the secondary by both mass and luminosity). There was, therefore, a phase of common-envelope evolution. Since the mass of Gl 781A is \(\approx 0.25 \, M_\odot\) and the original mass of Gl 781B was \(M \approx 1 \, M_\odot\) (since it has already evolved and cooled), it is clear that the mass ratio was greater than \(\approx 4\) when Gl 781B became a red giant and first engulfed the companion. Iben & Livio (1993) have reviewed this situation and shown that a common envelope will form and that the secondary (Gl 781A) will not accrete a significant amount of mass. After being engulfed, Gl 781A caused mass loss from Gl 781B, possibly ending B's evolution as an He white dwarf with relatively low mass \((\approx 0.4 \, M_\odot)\) instead of allowing B to become a CO white dwarf \((M \approx 0.6 \, M_\odot)\). This would be consistent with the estimate of \(i\) from the detected rotational broadening. The calculations of Iben, Tutukov, & Yungelson (1997) indicate that for systems with 12 hr periods, helium white dwarfs with very low mass \((M < 0.3 \, M_\odot)\) main-sequence companions should be about 7 times more common than CO white dwarfs with very low mass main-sequence companions.

3.2. Chromospheric and Coronal Activity

For M dwarfs, membership in a very close \((P \approx 5 \, \text{days})\) binary system is thought to be a sufficient condition for high chromospheric activity—rapid rotation at relatively old age is maintained by tidal interactions between the two stars (Bopp & Fekel 1977; Young, Sadjadi, & Harlan 1987). Both Gl 455 and Gl 781 prove to be short-period binaries, with Gl 781A having detectable rotation, and we therefore attribute their activity to their binary nature. Gl 781A's companion is not likely to affect the activity (except by being the cause of Gl 781A's rapid rotation). Although red dwarfs near hot white dwarfs show Hz emission due to reprocessing of the white dwarf's EUV flux in the chromosphere of the red dwarf (Schultz, Zuckerman, & Becklin 1996), Gl 781B's low luminosity \((M_V > 13)\) implies that it is not a significant source of EUV flux. Furthermore, Gl 781A's emission is not stronger from the hemisphere facing the white dwarf, since there is no correlation between the strength of Hz with orbital phase in the 1996 August data. The white dwarf is therefore not causing the emission by incident radiation or other line-of-sight effects. We also attribute the X-ray flux to a normal corona generated by Gl 781A's rapid rotation, rather than accretion onto the white dwarf, since at present Gl 781A is only about 10% of the size of its Roche lobe as estimated by Eggleton's (1983) formula. We note also that the X-ray flux is not caused by some sort of "basal" emission unique to subdwarfs, since none of the known sdM's and esM's without Hz emission are detected in X-rays by ROSAT.

Metal-poor stars are usually associated with an extremely old \((10^{10} \, \text{yr})\) population. Preston et al. (1994), however, have identified young, A-type, metal-poor main-sequence stars with large velocities, which they suggest are the residue of a merger with a satellite galaxy (or galaxies). Presumably these stars have lower mass counterparts, and if the M subdwarfs have emission lifetimes comparable to field M dwarfs' (Hayweld et al. 1996), then these young M subdwarfs will show detectable Hz emission. We cannot directly rule out either Gl 455 or Gl 781 as members of this young, metal-poor population. The cooling time for the white dwarf in Gl 781 is at least 2 Gyr, which is too long to maintain the observed rapid rotation if M subdwarfs lose angular momentum like field M dwarfs. Overall, the binary nature of the two systems appears to be sufficient to explain their activity.

The properties of sdM's relative to (near-solar metallicity) dMe's are important because they provide a unique perspective on the generation of strong activity. Gl 781A and Gl 455AB are the only known highly active, metal-poor, cool main-sequence stars. Gl 781A is of particular interest, because its high rotational velocity is similar to the rotational velocities observed in the Pleiades cluster.
members of the same mass (Jones, Fischer, & Stauffer 1996). In comparing the properties of the sdMe’s, it should be remembered that considerable dispersion exists in the chromospheric and coronal properties of even coeval, homogeneous samples such as the Pleiades and Hyades clusters, and that even larger dispersion exists in field samples. The physical causes of this dispersion are unknown. Thus any relations based upon only two systems must be viewed with caution.

We first note that the data suggest that the chromospheres and coronae of the sdMe’s are quite similar to disk dMe stars, despite the great metallicity difference between the two classes. The sdMe X-ray hardness ratios, which are sensitive to the coronal temperatures, are comparable to the field dMe’s with similar X-ray luminosities. The ratios of Hz to Hβ fluxes are similar to that seen in field dMe stars (Hawley et al. 1996; Gizis et al. 1998). The strength of the He D3 line is normal compared with the Hz line, as is the strength of the He 6678 Å line compared with the He D3 line. The correspondence between this sdMe and the dMe’s suggest that the physical properties (e.g., temperature) of the lower chromosphere (traced by the Balmer lines), upper chromosphere (helium lines), and corona (X-rays) do not depend strongly on metallicity.

We measure the overall activity of each star using the ratios of the X-ray luminosity (Lx) and the Hz luminosity (LHz) to the star’s bolometric luminosity. We focus on Gl 781A since we know the orbital period and v sin i, allowing a comparison with disk dMe stars with similar rotation rates. Gl 455A and 455B are more slowly rotating than Gl 781A, but the period is unknown.

Jones et al. (1996) have measured v sin i for M dwarfs in the Pleiades using the Keck I Telescope. The nine stars with 0.23 M⊙ ≤ M ≤ 0.29 M⊙, similar to Gl 781A’s mass of ~0.25 M⊙, have measured velocities in the range 8 km s⁻¹ ≤ v sin i ≤ 41 km s⁻¹. These results suggest that we can directly compare the metal-poor star Gl 781A with a population of stars with similar masses and rotation rates. Although this means two important parameters are the same, there are three notable differences between Gl 781A and the Pleiades stars: (1) Gl 781A’s age is most likely 10–15 Gyr and certainly is 2 Gyr or more, which is ~20 times the age of the Pleiades cluster; (2) Gl 781A is metal-poor ([M/H] ~ −1.2) whereas the Pleiades have near-solar metallicity; (3) Gl 781A’s companion might induce internal and surface differential rotation different from that of single stars (Young et al. 1987).

Direct comparison with the Pleiades star sample observed by Jones et al. (1996) is hampered by the small sample size and lack of X-ray data for most of their stars. We instead compare with the much larger survey of the Pleiades cluster reported by Hodgkin, Jameson, & Steele (1995). The Hodgkin et al. survival analysis of both detections and upper limits indicates that stars with masses near 0.25 M⊙ (Mf ~ 9) have mean log (Lx/Lbol) and log (LHz/Lbol) of ~ −3.3 and −3.7, respectively. The range in activity is large, as some detected stars have log (Lx/Lbol) ~ −2, while many stars have upper limits indicating log (Lx/Lbol) < −3.5. Gl 781A’s ratios are quite close to the mean values, and on this basis the activity of a rapidly rotating metal-poor star appears to be virtually identical to its more metal-rich counterparts—although factors of ~0.3 in the logarithm of the activity level cannot be ruled out. On the other hand, Gl 781A is an order of magnitude weaker in X-ray activity than the strongest M dwarfs in the Pleiades. As noted by Hodgkin et al. (1995), the reason these sources are stronger is unknown. Indeed, it interesting to note that many of the slowest rotators in the Jones et al. (1996) sample have the strongest Hz emission—an expanded data sample, to establish the nature of a rotation-activity relation for this stellar mass, would be of considerable interest. We finally note that the Hyades cluster offers another point of comparison with the sdMe sample. Again, the mean ratios of Lx/Lbol and LHz/Lbol for the Hyades M dwarfs (Reid, Hawley, & Mateo 1995b) are similar to the ratio seen in Gl 781A.

We may also compare the activity of the sdM binaries with that of nearby field dM binaries. Like the M subdwarfs, these M dwarfs have activity induced by the rapid rotation caused by very close companions. We have detected a further 16 SB2 M dwarf binaries using the same echelle configuration as used for the current observations (Gizis et al. 1998). None of these systems have v sin i as great as Gl 781A; all are likely to have orbital periods less than 5–10 days. Matching these objects with the ROSAT All-Sky Survey, we find that four have log (Lx/Lbol) < −3.3, whereas 12 have log (Lx/Lbol) > −3.3 [with four systems at the maximum of log (Lx/Lbol) ≈ −2.9]. If rotation were the most important parameter, one might expect Gl 781A to be as active in X-rays as the most active nearby binaries. In this case, Gl 781A would be deficient by about 0.4 in the log (a factor of 2.5). It should also be recalled that the range in observed Hz equivalent widths is 1.0–1.9, which suggests that some of the difference in activity level could be a result of Gl 781A’s happening to be in a relatively weak state at the time of the ROSAT observations. Schmitt et al. (1995) have found that, over a decade, M dwarfs, unlike the Sun, do not show variability in X-rays in excess of a factor of 2.

One of the most striking aspects of the sdMe data is that both systems show similar X-ray activity levels despite their different rotation rates. Gl 455AB certainly has a much slower rotation rate than Gl 781A; indeed, Lx/Lbol is much weaker in Gl 455AB. The simplest explanation is that the Gl 455AB X-ray observation is affected by a flare or other transient event. There are a few M dwarfs in the Hyades (Reid et al. 1995b) that have log (Lx/Lbol) ≈ −1 for non-simultaneous measurements, so Gl 455AB’s relative activity levels are not unprecedented.

Comparing the sdMe with the near-solar-mass Hyades binaries detected by Stern, Schmitt, & Kahabka (1995), Gl 781A has an X-ray activity level similar to that of the GK dwarf (B – V > 0.6) binaries with periods of a few days but is less active than the half-day–period binary V471 Tauri. Given the large mass differences, we conclude merely that this example suggests that it is not unreasonable to expect that Gl 781A’s half-day period should put it among the most active binaries—and therefore that Gl 781A may be mildly X-ray subluminous. There is, however, considerable evidence that the rotation-activity relationship is complex in low-mass stars (indeed, Hawley et al. 1996 questioned the existence of a correlation between rotation rate and activity level in M dwarfs). Stauffer et al. (1997) have found that for a sample of Hyades M dwarfs (M ~ 0.45 M⊙ above the fully convective limit and more massive than the sdMe’s) there is no single activity-rotation relation. They propose that their data can be explained as a “bifurcation” with two different rotation-activity relations. On one relation, relatively slowly rotating stars (v sin i < 6 km s⁻¹) can be as
active \([\log (L_{\text{X}}/L_{\text{bol}}) > -4.15]\) as stars (on the other relation) with 10 km s\(^{-1}\) \(\lesssim v \sin i \lesssim 15\) km s\(^{-1}\). They suggest that the difference is due to differing rotational evolution histories, which result in differing radial and latitudinal differential rotation. They also find that stars with companions as distant as 1 AU have enhanced activity relative to single stars with the same rotation rate. In addition, there is evidence that the most rapid \((P \lesssim 10\) hr\) GK rotators may weaken in activity level (Randich et al. 1996). Clearly, there are many parameters relevant to determining the activity level—these or others may be important for Gl 781A.

We conclude that Gl 781A does not show evidence for a significant (i.e., factor of 10) weakening in its activity levels relative to near-solar-metallicity stars. It may, however, be subluminous in X-rays for its bolometric luminosity by up to a factor of \(\sim 2.5\). This may be the result of its metal deficiency. Definite conclusions are prevented by the large, and as yet poorly understood, dispersion in the activity levels of M dwarfs. The relatively small effect on the X-ray emission due to a factor of deficiency in metals suggests that composition is not a major contributor to the dispersion in activity levels observed for M dwarfs, which are all relatively close to solar metallicity \([\langle \frac{M}{H} \rangle \gtrsim -0.6;\) Gizis 1997].

The Ottmann et al. (1997) survey of spectral type FGK metal-poor binaries has shown that a sample of Population II short-period binaries analogous to RS CVn binaries are at least 1 order of magnitude less X-ray luminous than the disk RS CVn binaries, although some Population II binaries are as luminous as the RS CVn binaries. They have suggested that the X-ray line emission is reduced as a result of the relative lack of metals in the coronae of Population II systems with \(-1.4 < [M/H] < -0.4\). Our sdMe's lie in the low-metallicity end of that range. Based upon our discussion above, we conclude that the sdMe's are not as X-ray–subluminous as expected by analogy to the Ottmann et al. results.

4. CONCLUSIONS

We have obtained spectra of two very low mass metal-poor halo systems that show Hz and X-ray emission. Both prove to be close binary systems, which accounts for their high activity level. We deduce that Gl 781A's unseen companion is a cool white dwarf. The present-day orbital period of 12 hr implies that the system passed through a phase of common-envelope evolution. Gl 455AB consists of two near–equal-luminosity sdMe.

The strength of the X-ray coronae of the sdMe's relative to the Hz chromosphere is well within the range observed in dMe stars in the field and in young clusters. Gl 781A's level of activity, as measured by the ratio \(L_{\text{X}}/L_{\text{bol}}\), is comparable to the mean activity level in the Pleiades. The comparison with both the Pleiades and field dMe binaries suggests that Gl 781A is no more than a factor of \(\sim 2.5\) subluminous in X-rays because of its metallicity. This is in contrast to the factor of 10 observed in most (but not all) stars in the Ottmann et al. (1997) survey of more massive metal-poor binaries.

With only two sdMe systems, these results are necessarily uncertain. Unfortunately, it will be difficult to significantly increase the sample of sdMe's and esdMe's, since the two systems discussed here are the only such binaries detected among a total of 68 LHS Catalogue sdM and esdM stars observed from Palomar (Gizis 1997; Gizis & Reid 1997a, 1997b). A more optimistic view, however, is that activity due to rapid rotation could allow the identification of, or place limits upon the existence of, short-period binaries and/or relatively young (few Gyr) halo populations, given a large spectroscopic sample.

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