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# The Extremely Active Single Giant 1E 1751+7046 = ET Draconis: Revised Properties and a Reevaluation of Its Evolutionary Status

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# THE EXTREMELY ACTIVE SINGLE GIANT 1E 1751+7046 = ET DRACONIS: REVISED PROPERTIES AND A REEVALUATION OF ITS EVOLUTIONARY STATUS

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## ABSTRACT

New spectroscopic observations have resulted in significant revisions to several of the orginally published properties of the X-ray bright, chromospherically active star 1E 1751+7046: the spectral classification has been revised from K5 IV to K0 III, $v \sin i$ from 30–40 km s$^{-1}$ to 23 km s$^{-1}$, and the reported nondetection of the Li I 6707 Å line to a significant log $\epsilon$(Li) = 1.8. Chromospheric and transition region surface fluxes from *IUE* observations and the coronal surface flux from earlier *Einstein* data are close to saturation levels, and comparable only to very active binaries, pre–main-sequence stars, and FK Comae itself. *IUE* observations also recorded a flare. Fifteen new radial velocity measurements show no evidence for a companion and are consistent with intermediate or young disk membership. On the other hand, we show the star to be located about 250 pc above the galactic plane, suggesting an intermediate or old disk object. The new spectral class ($T_{\rm eff}$) and limits on the luminosity indicate that 1E 1751+7046 is a low-mass star on its first ascent of the giant branch. Photometry from the Four College Consortium Automatic Photometry Telescope is consistent with the recently published photometric period of 13.98 days, and the light curve is well fitted by a model consisting of two large spots at latitudes of $\sim 30°$ and $\sim 50°$. There are currently only two possible evolutionary scenarios for this anomalous star: (a) coalescence from a progenitor W UMa–type contact binary; or (b) the dredge-up of both angular momentum and nuclear processed material in a low-mass ($\sim$1–2.5 $M_\odot$) giant. A space motion, obtainable once a parallax and proper motion are available from *Hipparcos*, may resolve the age (old disk-young disk) uncertainty: young disk motions would favor the angular momentum transfer scenario. There is no current theory that can account for the observed lithium abundance.

*Subject headings:* stars: abundances — stars: coronae — stars: evolution — stars: individual (1E 1751+7046) — stars: late-type

## 1. INTRODUCTION

1E 1751+7046 (=ET Dra; BD +70°959) initially attracted attention as one of three *Einstein* Medium Sensitivity Survey (MSS) coronal sources with anomalously high X-ray–to-optical flux ratios ($f_x/f_v$). In fact, it was the most extreme of the three, with $\log f_x/f_v = -0.8$ (Stocke et al. 1983). From subsequent optical observations Silva et al. (1985) classified it as K5 IV, estimated a $v \sin i$ value of 30–40 km s$^{-1}$, and noted Ca II H and K emission cores indicative of a chromospherically active star.

Based on the high galactic latitude ($b^{\rm II} = +30.8°$) and the lack of either radial-velocity variations or a detected lithium 6707 Å line in subsequent MMT observations, Fleming et al. (1987) concluded that the star is an evolved, single star. They corrected the previously published $m_v \simeq 13.1$ (Stocke et al. 1983) to $m_v \simeq 9.7$ and rederived the *Einstein* X-ray flux assuming a thermal spectrum appropriate for stellar coronae, rather than a power law as assumed by Silva et al. (1985). These changes resulted in $\log L_x/L_{\rm bol} \sim -3.5$, a value similar to the most active RS CVn systems (e.g., Topka et al. 1982; Helfand & Caillault 1982; Vaiana et al. 1981).

At radio wavelengths, 1E 1751+7046 was the only one of 28 late-type stars from the MSS detected at 6 cm with the VLA (Fleming et al. 1987). Subsequent VLA observations by Skinner (1991) determined that the radio emission is variable and probably nonthermal, and that the X-ray and radio properties resemble those of RS CVn binaries.

From the available data—a single, rapidly rotating, active, evolved star at relatively high galactic latitude ($b^{\rm II} = +30.8°$)—Fleming et al. concluded that 1E 1751+7046 was a prime candidate for a spun-down FK Comae star, i.e., most likely a coalesced (or coalescing) W UMa contact binary (Bopp & Stencel 1981; Guinan & Robinson 1986), which is losing angular momentum as a result of magnetized stellar winds.

Because of the sensitivity of higher temperature lines to magnetic activity, we obtained *IUE* observations of 1E 1751+7046 with the goal of comparing this star with the bizarre spectra of FK Com, and with other suggested spun-down FK Comae candidates such as HD 199178 (e.g., Neff, Vilhu, & Walter 1988) or NGC 188 I-1 (Harris & McClure 1985; Ambruster & Guinan 1997). We also obtained ground-based optical spectroscopic observations with the coudé feed telescope at Kitt Peak National Observatory (KPNO), and the 1.2 m and 1.8 m telescopes at Dominion

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TABLE 1

OBSERVED PROPERTIES OF 1E 1751+7046

| | |
|---|---|
| Positional | |
| R.A. (2000) | $17^h50^m25\overset{s}{.}10$ |
| Decl. (2000) | $+70°45'36''.5$ |
| $l^{II}$ | $101\overset{\circ}{.}5$ |
| $b^{II}$ | $+30\overset{\circ}{.}8$ |
| Spectroscopic | |
| Spectral type | K0 III[a] |
| $v \sin i$ | 23 km $s^{-1}$ [b] |
| RV | $-12.3 \pm 0.3$ km $s^{-1}$ [b] |
| log $\epsilon$(Li) | 1.8[a] |
| Photometric | |
| $m_v$ | $9.642 \pm 0.019$[b] |
| $(B-V)$ | $1.102 \pm 0.010$[b] |
| $(U-B)$ | $0.852 \pm 0.015$[b] |
| $P_{rot}$ | $13\overset{d}{.}982$[c] |
| UV, X-Ray, and Radio | |
| $f_{Mg\,II}$ | $9.9 \pm 1.9 \times 10^{-13}$ ergs $cm^{-2}$ $s^{-1}$ [b] |
| $f_{C\,IV}$ | $6.0 \times 10^{-14}$ ergs $cm^{-2}$ $s^{-1}$ [b] |
| $f_x$ | $2.54 \times 10^{-12}$ ergs $cm^{-2}$ $s^{-1}$ [d] |
| $L_{5\,GHz}$ | $10^{17}$ ergs $s^{-1}$ $Hz^{-1}$ [d] |

[a] Fekel & Balachandran 1993.
[b] This paper.
[c] Jetsu et al. 1992.
[d] Fleming et al. 1987.

TABLE 2

*IUE* OBSERVATIONS OF 1E 1751+7046

| Image Number | Observation Date UT (yr, day, hr:min) | Exposure Time (minutes) | Observer |
|---|---|---|---|
| LWP13810L | 1988, 221, 14:21 | 35 | Hrivnak |
| LWP15760L | 1989, 171, 06:31 | 15 | Linsky |
| LWP15807L | 1989, 179, 06:20 | 45 | Ambruster |
| LWP15808L | 1989, 179, 14:49 | 35 | Ambruster |
| LWP15809L | 1989, 179, 16:22 | 30 | Ambruster |
| LWP17455H | 1990, 061, 17:27 | 150 | Ambruster |
| LWP18680L | 1990, 242, 12:17 | 25 | Ambruster |
| LWP18838L | 1990, 264, 10:37 | 26 | Ambruster |
| SWP36559L | 1989, 171, 10:49 | 450 | Linsky |
| SWP36582L | 1989, 179, 10:31 | 440 | Ambruster |

Astrophysical Observatory (DAO), as well as two seasons of *UBVRI* photometry.

The *IUE* and KPNO coudé feed observations extend, and in some cases significantly alter, the previously reported properties of 1E 1751+7046. An updated list of observed properties is given in Table 1. From the new data, we suggest that another interpretation besides that of a spun-down FK Comae star is possible.

## 2. OBSERVATIONS AND ANALYSIS

### 2.1. *Ultraviolet Emission-Line Surface Fluxes*

We acquire eight new ultraviolet spectra of 1E 1751+7046 with the *International Ultraviolet Explorer* (*IUE*) satellite between 1988 and 1990, including one deep 440 minute low-dispersion SWP spectrum (1100 Å–2000 Å; resolution = 6 Å), and one high-dispersion LWP spectrum (2000 Å–3000 Å; resolution = 0.1–0.2 Å). They are listed in Table 2 along with two additional spectra from the *IUE* archives, which we remeasured and included in our analysis. The data were reduced with standard *IUE* software.

Surface fluxes were computed with the Barnes-Evans relation (Barnes, Evans, & Moffett 1978; Linsky et al. 1982), and the $B-V$ color index from our KPNO photometry (Table 1). Use of the $B-V$ color index is preferable to the more frequently used $V-R$ index in the case of chromospherically active stars because these stars tend to have a $V-R$ color excess (Fekel, Moffett, & Henry 1986). The ultraviolet surface fluxes are listed in Tables 3 and 4.

### 2.2. *Optical Spectroscopy and Radial Velocities*

From 1991 April to 1993 April, seven spectrograms of 1E 1751+7046 were obtained (by F. C. F.) at KPNO with the coudé feed telescope, coudé spectrograph, and a TI CCD detector. One observation was centered at 6695 Å to detect the Li line while the rest were centered at 6430 Å. Each observation covers a wavelength range of 80 Å with a resolution of 0.21 Å.

Eight observations of 1E 1751+7046 were obtained in 1992 and 1993 at the DAO with the 1.2 m telescope (by B. J. H.). The radial-velocity spectrometer (RVS) was used at the coudé focus. In addition, three spectra were obtained on 1988 October 10 with the DAO 1.8 m telescope equipped with a Cassegrain spectrograph and intensified Reticon detector. These cover the spectral range 3920–4330 Å, with a resolution of $\sim$1 Å, and show strong Ca II H and K emission (Fig. 1).

Details of the velocity-reduction procedure for the KPNO spectra have been given by Fekel, Bopp, & Lacy (1978). The velocities were determined relative to International Astronomical Union (IAU) radial-velocity standard stars (Pearce 1957), or to $\mu$ Her. We assumed velocities of $-12.2$ km $s^{-1}$ for $\beta$ Oph, 5.6 km $s^{-1}$ for $\iota$ Psc (Scarfe, Batten, & Fletcher 1990), and $-16.4$ km $s^{-1}$ for $\mu$ Her (Stockton & Fekel 1992).

To obtain radial-velocity measurements with the DAO RVS, a physical mask is moved in front of the stellar spectrum, and a photocell measures the total transmitted light at various mask positions. The velocity of the star is then determined from a parabolic fit to the position of the minimum in the transmitted light. See McClure et al. (1985) for a more complete description of the instrument. These radial-velocity observations were made in conjunction with a project by one of us (B. J. H.) to measure the radial velocity of F supergiants, and accordingly a mask based upon an

TABLE 3

ULTRAVIOLET SURFACE FLUXES FOR 1E 1751+7046 ($10^5$ ergs $cm^{-2}$ $s^{-1}$)

| Image Number | N V (1240 Å) | O I (1305 Å) | C II (1335 Å) | Si IV (1400 Å) | C IV (1549 Å) | He II (1640 Å) | C I (1657 Å) | Si II (1810 Å) |
|---|---|---|---|---|---|---|---|---|
| SWP 36559L | 2.1 | 2.1 | 1.9 | 2.5 | 4.9 | 1.5 | ... | 1.3 |
| SWP 36582L | 1.2 | 1.6 | 1.8 | 1.1 | 2.3 | <2.6[a] | ... | 1.5 |

[a] Contaminated by nearby hit.

NOTE.—$F/f = 3.91 \times 10^{18}$ from Barnes-Evans $(B-V)$ relationship.

TABLE 4

VARIABLE Mg II $h + k$ SURFACE FLUXES

| Image Number | JD (2,440,000.0+) | $F_{\rm Mg\,II}$ ($10^6$ ergs cm$^{-2}$ s$^{-1}$) |
|---|---|---|
| L13810L...... | 7382.098 | 4.1 |
| L15760L...... | 7697.772 | 3.2 |
| L15807L...... | 7705.764 | 4.0 |
| L15808L...... | 7706.104 | 4.7 |
| L15809L...... | 7706.176 | 4.8 |
| L18680L...... | 8134.012 | 3.5 |
| L18838L...... | 8155.942 | 2.8 |

NOTE.—$F/f = 3.91 \times 10^8$ from Barnes-Evans $(B-V)$ relation.

F star was used. However, this spectral difference with 1E 1751+7046 causes no systematic errors in the velocities, since the F mask uses 340 of the sharper lines and avoids the strong hydrogen lines that dominate an F star spectrum. In fact, with this mask one routinely uses K-type radial-velocity standards, in addition to F and G, to monitor the instrumental zero point. These observations are tied into the radial-velocity standard system of the DAO 9286 m camera, which is very close to the IAU system, through nightly observations of IAU radial-velocity standards from the list of Scarfe et al. (1990). An F star mask correction of $-0.8$ km s$^{-1}$ and small nightly zero-point corrections ($\leq 0.2$ km s$^{-1}$) are applied. The resultant velocities are on the IAU system, and the standard error is derived from the fit to the minimum of the RVS observation combined with the small uncertainty in the nightly zero point.

The 15 new radial velocities, along with the heliocentric time of midobservation, are listed in Table 5. We have also listed for completeness the radial velocities of Fleming et al. (1987), and of Silva et al. (1985) as rereduced by Fleming et al. (1987); we discuss the radial velocity data more thoroughly in § 3.8 below. From our observations only, the average radial velocity is $-12.3 \pm 0.1$ (Table 1).

### 2.3. *Optical Photometry*

Absolute *UBV* photometry of 1E 1751+7046 was obtained on four of six consecutive nights at KPNO in 1989 October (by C. W. A.) with the AFP2 photometer on the no. 2 0.9 m. On each night at least 20 Landolt standard stars (Landolt 1983) were observed. The data were reduced with

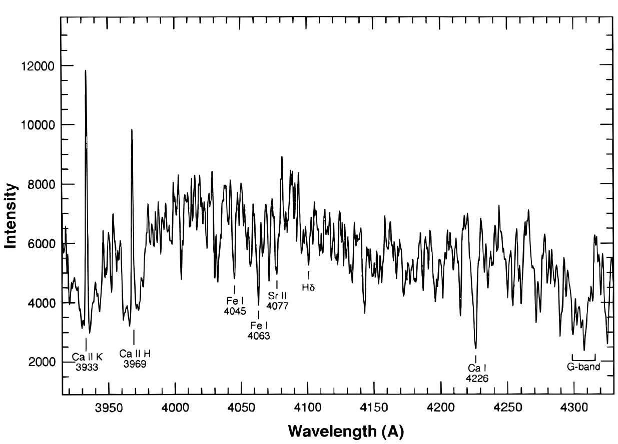


FIG. 1.—Medium-resolution spectrum of 1E 1751+7046, obtained on 1988 October 10 with the DAO 1.8 m telescope with a Cassegrain spectrograph and intensified Reticon detector. The intensity scale is arbitrary. Note the strong Ca II H and K emission cores.

TABLE 5

RADIAL VELOCITIES FOR 1E 1751+7046

| HJD (244+) | RV (km s$^{-1}$) | Phase (photometric) | Phase ("orbital") |
|---|---|---|---|
| 5503.76 ........ | $-11.50 \pm 0.66$[a] | 0.13 | 0.38 |
| 5504.96 ........ | $-9.90 \pm 0.68$[a] | 0.21 | 0.47 |
| 6537.96 ........ | $-13.10 \pm 0.64$[b] | 0.09 | 0.72 |
| 6569.81 ........ | $-14.92 \pm 0.63$[b] | 0.37 | 0.01 |
| 6635.86 ........ | $-14.24 \pm 1.02$[b] | 0.09 | 0.76 |
| 6636.82 ........ | $-14.82 \pm 1.03$[b] | 0.16 | 0.83 |
| 6637.65 ........ | $-14.25 \pm 0.71$[b] | 0.22 | 0.89 |
| 6638.64 ........ | $-15.59 \pm 0.73$[b] | 0.29 | 0.96 |
| 6639.64 ........ | $-17.00 \pm 0.92$[b] | 0.36 | 0.03 |
| 6640.64 ........ | $-16.00 \pm 0.81$[b] | 0.44 | 0.10 |
| 8347.949 ....... | $-11.70 \pm 0.7$[c] | 0.54 | 0.83 |
| 8427.844 ....... | $-12.4 \pm 0.7$[c] | 0.26 | 0.57 |
| 8714.8982...... | $-13.09 \pm 0.84$[d] | 0.79 | 0.20 |
| 8719.8675...... | $-12.99 \pm 0.74$[d] | 0.14 | 0.56 |
| 8733.8025...... | $-12.49 \pm 0.60$[d] | 0.14 | 0.56 |
| 8736.8006...... | $-13.32 \pm 0.71$[d] | 0.35 | 0.78 |
| 8770.882 ....... | $-13.5 \pm 0.7$[c] | 0.79 | 0.23 |
| 8773.951 ....... | $-13.1 \pm 0.7$[c] | 0.01 | 0.45 |
| 8799.8198...... | $-12.47 \pm 0.70$[d] | 0.86 | 0.31 |
| 8913.5857...... | $-11.9 \pm 1.0$[c] | 0.00 | 0.48 |
| 8914.5984...... | $-11.0 \pm 1.0$[c] | 0.07 | 0.56 |
| 9103.9364...... | $-11.2 \pm 0.7$[c] | 0.61 | 0.17 |
| 9130.8044...... | $-11.04 \pm 0.66$[d] | 0.53 | 0.10 |
| 9163.8481...... | $-13.92 \pm 0.77$[d] | 0.90 | 0.47 |
| 9168.9189...... | $-10.15 \pm 0.65$[d] | 0.26 | 0.84 |

[a] Silva et al. 1985.
[b] Fleming et al. 1987.
[c] F. C. Fekel, this paper.
[d] B. J. Hrivnak, this paper.

the method of Harris, Pim Fitzgerald, & Cameron Reed (1981). The comparison and check stars were SAO 8937 and SAO 8942, respectively. The typical error for an individual observation is 0.006 mag in $V$; three observations were generally made on each night and were averaged into a single datum.

Differential *UBVRI* photoelectric photometry of 1E 1751+7046 was obtained with the Four College Consortium 0.8 m Automated Photometry Telescope (APT) located on Mount Hopkins, AZ. The observations were obtained on seven nights during 1991 May and June, and seven nights in 1993. The same comparison star (SAO 8937) and check star (SAO 8942) were used. Observations on each night typically consisted of three to four *sky-comparison-variable-comparison* sets in which six to eight 10 s integration measures of the variable star were obtained in each filter during each set. The standard data reduction procedure is discussed in Guinan, McCook, & McMullin (1986). Typical errors for the nightly means were 0.007 mag in $V$ and 0.008 mag in $B$.

## 3. RESULTS AND STELLAR PROPERTIES

### 3.1. *Spectral Classification*

The revised spectral classification of K0 III (Ambruster, Guinan, & Siah 1991; Fekel & Balachandran 1993) for 1E 1751+7046 corresponds to $T_{\rm eff} = 4820$ K (Bell & Gustafsson 1989). It was determined from our KPNO spectrograms by a spectrum-comparison technique (Strassmeier & Fekel 1990), in which luminosity-sensitive and temperature-sensitive line ratios in the 6430 Å region, along with the general appearance of the spectrum, were used. The spectrum was compared with the appropriately broadened spectra of the K0–K2 III or IV stars listed by Strassmeier &

Fekel (1990). The best fit to 1E 1751+7046 was with the spectrum of $\beta$ Gem (K0 IIIb), which has [Fe/H] = $0.01 \pm 0.03$ (Taylor 1991), although a fit with $\kappa$ CrB (K1 IVa; [Fe/H] = $0.18 \pm 0.11$) was almost as good. Our classification is consistent both with the photometric classification of Jetsu et al. (1992), and with the observed $B-V$ color of the star which, if assumed to be unreddened, corresponds to a spectral type of about K1 III (Johnson 1966). Classification as a giant is further confirmed by the width of the Mg II $k$ line in the *IUE* high-dispersion spectrum (2.2–2.3 Å at the base), near the upper end of the range for giants (Ayres 1993).

One other comparison is of note. Our spectra of 1E 1751+7046 were also compared to an appropriately broadened spectrum of HR 1907, classified as K0 IIIb by Keenan & McNeil (1989). This star is an old disk (OD) giant with a space motion greater than 100 km $s^{-1}$ and moderate metal deficiencies (Shetrone, Sneden, & Pilachowski 1993). Its iron abundance is reduced by about a factor of 3–5 relative to the Sun's (Shetrone et al. 1993; Cottrell & Sneden 1986). The weak lines, as well as many of the strong lines, of HR 1907 were significantly weaker than the same lines in the spectrum of 1E 1751+7046. This suggests that 1E 1751+7046 is not as metal deficient as most OD giants; rather, its abundances are approximately solar.

Our classification of 1E 1751+7046 as K0 III is significantly different from the K5 IV classification of Fleming et al. (1987), based upon their low-resolution (7 Å) spectra. As we show later, this new classification yields a more consistent fit with the calculated physical properties.

### 3.2. *Projected Rotational Velocity* ($v$ sin $i$)

Ambruster et al. (1991) and Fekel & Balachandran (1993) reported $v \sin i = 19$ km $s^{-1}$, a value significantly less than the earlier estimated value of 30–40 km $s^{-1}$ (Silva et al. 1985). We have since revised this value upward slightly, to $v \sin i = 23$ km $s^{-1}$, in the course of adjusting it to the rotational-velocity scale of Gray (e.g., Gray 1989). We did this by measuring the FWHM for several relatively unblended lines in the 6430 Å region for 50 of Gray's stars for which we also have observations, then plotting these FWHMs against Gray's total broadening (which includes macroturbulence and $v$ sin $i$), and determining the best-fit polynomial. Applying this polynomial to the measured FWHMs for 1E 1751+7046 gives a total line broadening of 23.5 km $s^{-1}$ for the star. An assumed root-mean-squared macroturbulent broadening of 3 km $s^{-1}$ for late G and early K giants (Gray 1982, 1989) results in $v \sin i = 23$ km $s^{-1}$. It is certainly conceivable, however, that chromospherically active stars might have larger macroturbulent velocities than those of inactive stars. A macroturbulent velocity as large as 6 km $s^{-1}$ only reduces $v$ sin $i$ to 22.7 km $s^{-1}$. Thus, the $v$ sin $i$ value of 1E 1751+7046 is not particularly sensitive to the assumed macroturbulence, and we find $v \sin i = 23 \pm 1$ km $s^{-1}$ (estimated error).

### 3.3. *Lithium Abundance*

Even after accounting for blends, the strength of the Li 6707 Å line is significant (Fig. 2): the equivalent width is $90 \pm 5$ mÅ. (This EW is not large enough for non-LTE corrections to be important.) From spectrum synthesis Fekel & Balachandran (1993) determined a log Li abundance of 1.8, replacing the earlier value of log $\epsilon$(Li) = 1.6 reported in Ambruster, Fekel, & Guinan (1992). Such an

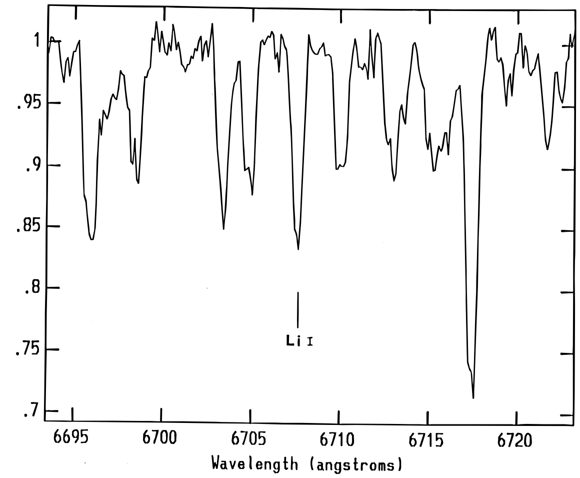


FIG. 2.—Spectrum of 1E 1751+7046 taken at the KPNO coudé feed, showing a significant (90 mÅ) Li I ($\lambda$6707) line, which translates to a log $\epsilon$(Li) = 1.8.

abundance is above the theoretical upper limit for a giant star, even one that has experienced no Li depletion on the main sequence. Brown et al. (1989) reported that only 4% of nearly 650 normal G and K giants examined for Li have log $\epsilon$(Li) > 1.3, although recent studies find that anomalously high Li abundances occur much more frequently (12%–33%) in chromospherically active giants (Randich, Gratton, & Pallavicini 1993; Fekel & Balachandran 1993).

### 3.4. *Ultraviolet Fluxes and Flaring*

The UV and coronal surface fluxes for 1E 1751+7046 (Tables 3, 4) are unusually high. In Figures 3, 4, and 5, we have plotted the quiescent Mg II $\lambda$2800, C IV $\lambda$1549, and X-ray surface fluxes ($F_{\rm Mg\,II}$, $F_{\rm C\,IV}$, and $F_x$) onto Vilhu's (1987) plots of surface flux versus color. All three, but particularly the coronal fluxes, fall close to the saturation level, defined as complete coverage of the stellar surface (i.e., filling factor = 1) by 1–2 kG magnetic fields (Vilhu 1987). In fact, the only comparably active stars are very active binaries, pre–main-sequence T Tauri and naked T Tauri (NTT) stars, and FK Com itself.

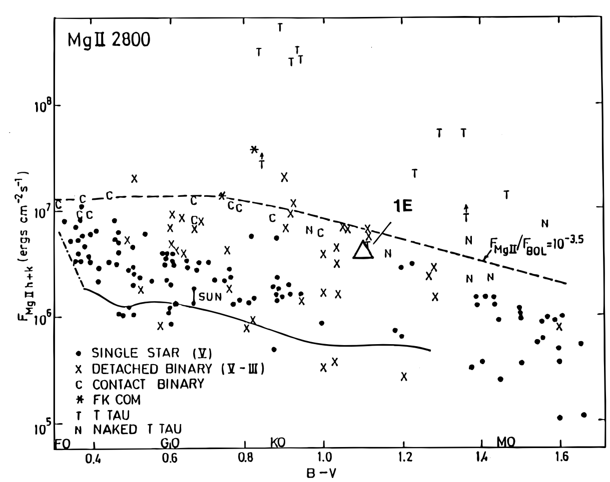


FIG. 3.—Mg II $\lambda$2800 surface flux 1E 1751+7046 plotted on Fig. 3 of Vilhu (1987). The saturation level is indicated by the dashed line. The only other stars with similarly high surface fluxes are RS CVn binaries, T Tauri, and NTT stars.

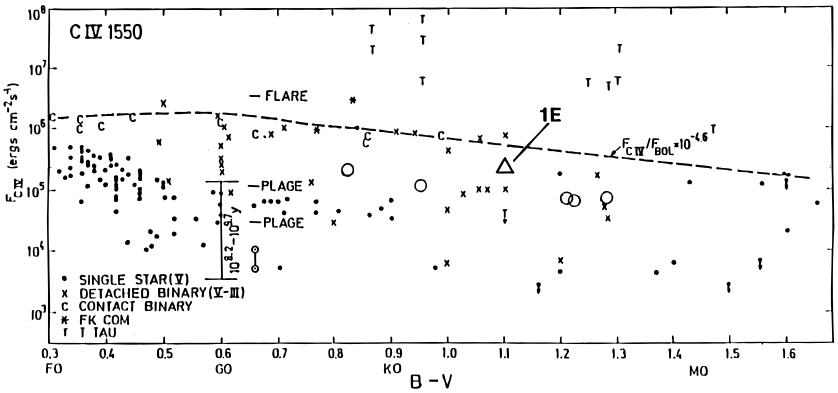


FIG. 4.—C IV $\lambda$1549 surface flux for 1E 1751+7046, plotted on Fig. 5 of Vilhu (1987) is comparable to the highest RS CVn surface fluxes and, when corrected for temperature differences, is comparable to FK Com. The saturation level is indicated by the dashed line. The C IV surface fluxes for the five single, Li-rich, chromospherically active giants of Fekel & Balachandran (1993) (plotted as open circles) are all lower.

Furthermore, the transition region (TR) fluxes (N V $\lambda$1240, Si IV $\lambda$1400, and C IV $\lambda$1549) are variable (Fig. 6 and Table 3): they are a factor $\sim$2 higher in SWP 36559L than in SWP 36582L, which was taken 8 days ($\sim$0.5 in phase) earlier. This is well outside conservative 25% errors. Either the star flared, or a major active region rotated onto the facing hemisphere. However, in the case of an active region, we should expect to find a similar rise in the chromospheric fluxes (O I $\lambda$1305, Si II $\lambda$1820). Since we do not (Table 3), a flare is the more likely explanation. The lower, presumably quiescent, C IV value is plotted in Figure 4.

The Mg II $\lambda$2800 surface fluxes (Table 4) show low level but significantly variability (Ambruster et al. 1992); the range in flux exceeds a factor 1.5, which is outside conservative errors of 15%. Such variability in the chromospheric Mg II fluxes is somewhat unusual, even for active stars. There was no simultaneous optical coverage so it is not known how much of this scatter might be due to flaring.

The Mg II line profiles in the underexposed high-dispersion LWP spectrum (Table 2) do not appear particularly unusual; specifically, they do not show the bizarre characteristics of Mg II profiles from FK Com (e.g., Walter et al. 1984).

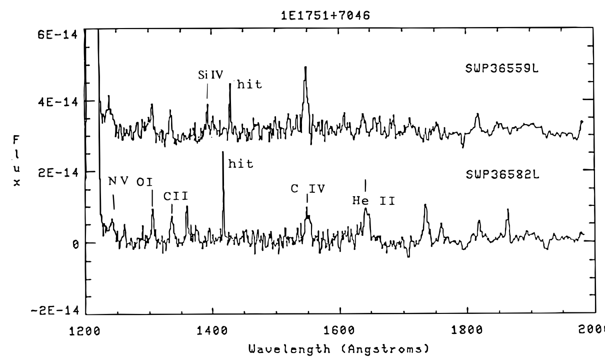


FIG. 6.—Ultraviolet flare spectrum SWP 36559L (*top*), compared with the quiescent spectrum SWP 36582L (*bottom*). SWP 36559L was shifted in flux by an arbitrary amount for comparison purposes. The surface fluxes for the TR lines N V ($\lambda$1240). Si IV ($\lambda$1400), and C IV ($\lambda$1549) are enhanced by a factor $\sim$2 in SWP 36559L (see Table 3). The spiky features near 1420 Å in both spectra are cosmic-ray hits; the apparently larger flux of the He II $\lambda$1640 line in SWP 36582L is also caused by contamination from a hit.

### 3.5. *Light Curve, Rotation Period, and Spot Modeling*

Photometric observations of 1E 1751+7046 taken over 3 months in 1988 with the Villanova 0.38 m telescope showed low-amplitude variability ($\Delta V \sim 0.03$ mag), and hinted at a

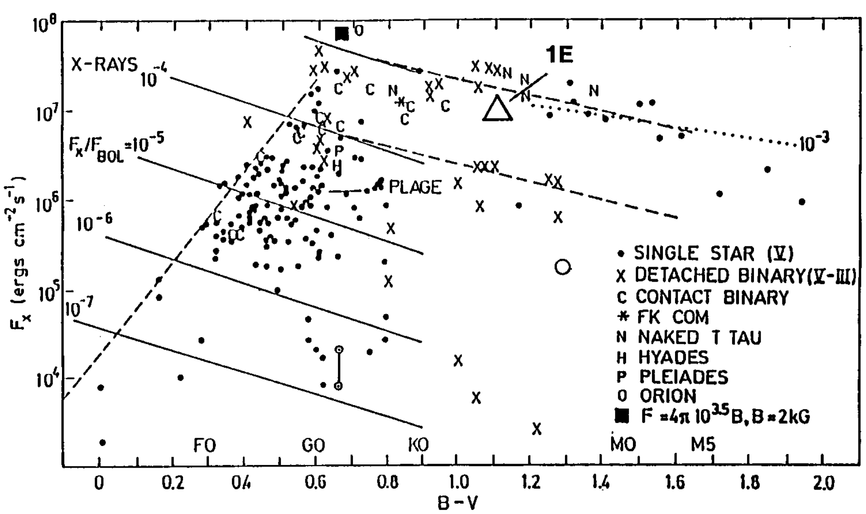


FIG. 5.—0.3–3.5 keV X-ray surface flux for 1E 1751+7046, plotted on Fig. 6 of Vilhu (1987), is comparable to FK Com. This is almost certainly a quiescent flux, since three different *Einstein* observations show no evidence for variability (Garcia 1992). Saturation boundaries are indicated by the dashed lines, and several lines of constant $F_x/F_{bol}$ are shown. Also plotted as an open circle is the much lower X-ray surface flux for HD 31993 (Gioia et al. 1990), the only one of the five rapidly rotating, Li-rich, single giants with a published $L_x$.

~5 day period (Bergin et al. 1988).

One year later (1989 October), limited KPNO photometry (four observations over six consecutive nights) continued to show modest brightness variations: $\Delta V = 0.04$ mag (where nightly errors were $\leq 0.006$ mag). The average $V$ magnitude and colors are listed in Table 1.

By the end of 1989, only 1 or 2 months after the KPNO observations, the variability amplitude had increased dramatically by almost an order of magnitude to $\Delta V \simeq 0.25$ mag, and finally a convincing rotation period of $13^{\rm d}.982$ could be determined (Jetsu et al. 1992). Both phase-linked color changes (Jetsu et al.) and the relatively large amplitude of the light curves support a starspot origin for the modulation. Similar changes in amplitude have been seen in active single and binary BY-Draconis-type stars and in active RS CVns, and most likely indicate a major redistribution of the various starspot regions.

Our APT *UBVRI* observations from Mount Hopkins show that the variability amplitude has remained high now for several years: $\Delta V \simeq 0.22$ mag in 1991 and $\Delta V \simeq 0.17$ mag in 1993. Those data, although limited, by chance cover both the maximum and minimum phases of the light curve in both years and are consistent with the $13^{\rm d}.982$ period. The nightly means for the $B$ and $V$ observations, phased with the $13^{\rm d}.982$ period, are plotted in Figure 7.

The 1991 *UBVRI* light curves of 1E 1751+7046 were successfully modeled using the Binary Marker code (Bradstreet 1991), with the mass and luminosity of the program's second star set to zero (see Fig. 7). We adopted a photospheric temperature of 4800 K, consistent with the K0 III spectral classification, and an inclination of the rotation pole to the line of sight of $i \approx 60°$. (The observed rotation period of $\sim 13^{\rm d}.982$, the $v \sin i = 23$ km s$^{-1}$, and the calculated radius range imply an inclination $30° \leq i \leq 90°$.)

Because of the few observations defining the light curves, only approximate spot parameters can be found. Nevertheless, two large, dark spots, 25°–30° in extent and separated in stellar longitude by $\approx 110°$ were found to fit the light curves well. The spot temperature, the best determined parameter from the modeling, was determined from the wavelength dependence of the light variations to be $\Delta T_{\rm photo\text{-}spot} \simeq 700$ K. These spot sizes and temperatures are typical of stars with very high $L_x$ and UV fluxes (Guinan & Giménez 1993).

It should be kept in mind, however, that the photometric starspot solution models the *maximum* brightness contrast over the star. Based on the very high chromospheric activity levels observed for 1E 1751+7046, it is likely that the star is heavily spotted and that the observed light variations arise from a greater concentration of spots on one hemisphere of the star than the other. Thus the present solution most likely gives the *minimum* surface area of the star covered with spots.

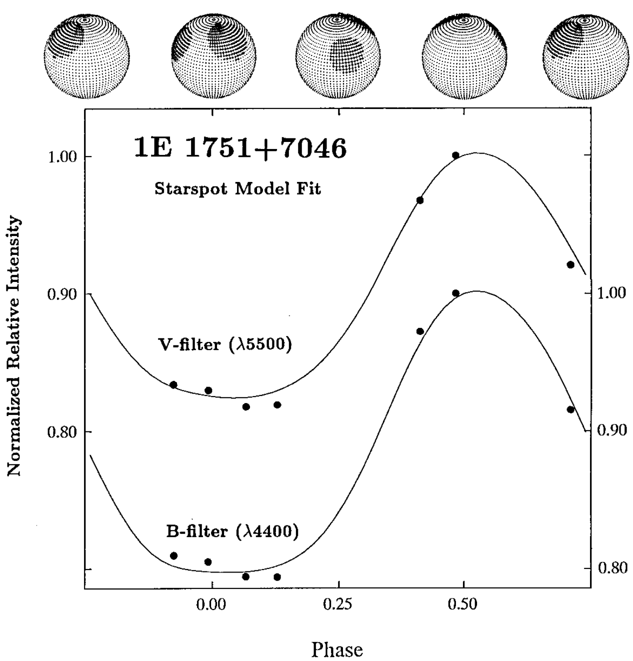


FIG. 7.—$B$ and $V$ light curves and spot model for 1E 1751+7046 from observations with the 0.8 m FCC APT on Mount Hopkins, AZ. The $U$, $R$, and $I$ light curves are similar. An arbitrary epoch was chosen so that minimum brightness occurs near zero phase. The relatively large amplitude of the light curve is similar to that found by Jetsu et al. (1992), and an order of magnitude greater than was present in 1988 and much of 1989. Because of the large sizes and high latitudes the spots are never completely out of view even at maximum light.

### 3.6. *Calculated Physical Properties*

Even without a known parallax, it is possible to set relatively tight constraints on many of the most important physical properties of 1E 1751+7046 from the surface temperature ($T = 4820$ K), the $13^{\rm d}.982$ rotation period (Jetsu et al. 1992), and the revised $v \sin i$ of 23 km s$^{-1}$. These stellar properties are listed in Table 6. The observational constraints on $i$, $30° \leq i \leq 90°$ (see above), determined the range for the various stellar properties. The distance follows from the luminosity, which was calculated from the radius, the temperature, and an assumed reddening of 0.2 mag.

The $z$-distance above the galactic plane follows from the constraints on the distance, and from $b^{\rm II} = +30°.8$ (Table 1). The *Einstein* flux from Fleming et al. (listed in Table 1) was used to calculate $L_x$ and $F_x$. $F_{\rm Mg\,II}$ is the mean of the surface fluxes in Table 4.

The ranges in radius and luminosity agree with the K0 III spectral type. The X-ray to optical flux ratio, first corrected by Fleming et al. (1987), is little changed by the new stellar parameters; we derive $\log (f_x/f_v) = -3.4$, which is still at the upper end of the range for RS CVn stars (Walter & Bowyer 1981).

The abundances and low radial velocity of 1E 1751+7046 are consistent with a young disk object. However, the star's relatively large distance above the galactic plane suggests intermediate or even OD population (Mihalas & Binney 1981). In fact, the $z$-distance of 1E 1751+7046 (160–320 pc) overlaps that of FK Com ($z = 245 \pm 50$ pc), an established OD star (Dorren, Guinan, & McCook 1984).

TABLE 6

PHYSICAL PROPERTIES OF 1E 1751+7046

| |
|---|
| $6.4\ R_\odot < R < 12.7\ R_\odot$ |
| $19.6\ L_\odot < L < 78.6\ L_\odot$ |
| $+2.0 > M_v > +0.5$ |
| 310 pc < $d$ < 630 pc |
| 160 pc < $z$ < 320 pc |
| $3.0 \times 10^{31}$ ergs s$^{-1}$ < $L_x$ < $1.2 \times 10^{32}$ ergs s$^{-1}$ |
| $F_{\rm Mg\,II} = 3.9 \pm 0.7 \times 10^6$ ergs cm$^{-2}$ s$^{-1}$ |
| $F_{\rm C\,IV} = 2.3 \times 10^5$ ergs cm$^{-2}$ s$^{-1}$ |
| $F_x = 9.90 \times 10^6$ ergs cm$^{-2}$ s$^{-1}$ |
| $\log f_x/f_v = -3.4$ |

### 3.7. *Constraints on the Mass*

It is highly likely that 1E 1751 + 7046 is a low-mass giant. The star's $T_{eff}$, which is well determined from its spectral class, and its luminosity range (Table 6), when plotted on the grid of recent evolutionary models of Schaller et al. (1992), imply 2.5 $M_\odot \gtrsim M_* \gtrsim 1\ M_\odot$, depending on metallicity. Assuming solar metallicity, as indicated by our spectral comparisons, 1E 1751 + 7046 would be close to the base of the giant branch as a 1.5–2 $M_\odot$ star.

### 3.8. *Single or Binary?*

Our radial-velocity data confirm the finding of both Fleming et al. (1987) and Silva et al. (1985) that 1E 1751 + 7046 is a single star. In plotting their radial-velocity data against the $13^{d}.982$ day photometric period, however, Jetsu et al. (1992) noted an apparent phase-dependent modulation that suggested a radial-velocity period of $13^{d}.912$. If real, this would reflect an essentially synchronous orbit around a companion: chromospherically active stars are considered synchronously rotating if the two periods agree to within about 5%. Within that limit, latitudinal differential rotation, as on the Sun, would assure that some parts of the two stars are synchronously rotating.

In Table 5, we have phased all the radial-velocity data, including the new DAO and KPNO measurements, to both periods (rotational and "orbital") using the ephemerides in Jetsu et al. and plotted them in Figures 8*a* and 8*b*. The new observations have good phase coverage and show little variability. In fact, the mean of the Fekel velocities agrees with the means of both the Silva et al. and Hrivnak velocities with their errors (Table 5). A closer examination reveals that all the evidence for the trend found by Jetsu et al. comes from the Fleming et al. velocities, which are systematically more negative than those of the other observers. Six of their eight radial velocities were taken on consecutive nights (Table 5) and show an increasingly negative trend over that period. Whether this is an artifact of their data reduction and analysis process in the case of a broad-lined and highly chromospherically active star, or has a physical explanation, remains to be seen. We conclude that the data published to date are consistent with the assumption that 1E 1751 + 7046 is a single star.

Additional velocity observations are being obtained by Stefanik (1992), who reports that ~30 radial-velocity measurements taken over ~1000 days with the 1.5 m Wyeth reflector at the Oak Ridge Observatory in Harvard, Massachusetts, appear to show low-amplitude variations (mean RV = $-11.9 \pm 1.9$ km s$^{-1}$). However, no periodicity close to the $13^{d}.982$ rotation period has been found and the variations so far appear to be nonperiodic. Our observation on JD 2,449,163 (Table 5) may be an example of this kind of scatter, which is somewhat outside 1 $\sigma$ errors and for which no explanation can be found in either the data-taking or data-reduction processes. Because of the lack of any clear periodicities, we suspect that this low-level radial-velocity variability results from changing spot intensities and distributions on the star's surface: large spot groups near the limbs, in particular, can alter the line shapes (e.g., Fekel 1983) and thus the measured velocities. Nevertheless, even if 1E 1751 + 7046 is eventually found to have a companion, the data to date are sufficient to establish that the period must be long, the companion distant, and the evolution of 1E 1751 + 7046 therefore unaffected.

## 4. DISCUSSION

Our new observations and results show that the physical properties of 1E 1751 + 7046 are significantly different from those determined by Fleming et al. (1987). We examine three possibilities for its evolutionary history and current status: (1) that 1E 1751 + 7046 is a pre–main-sequence (pre-MS) star; (2) that, as suggested by Fleming et al. (1987), it is a post–main-sequence (post-MS) coalesced binary similar to FK Com; and (3) that it is a post-MS giant with rapid rotation provided by core angular-momentum transfer.

### 4.1. *Pre-Main-Sequence Option*

Although pre-MS stars have strong activity and large Li abundances, the possibility that 1E 1751 + 7046 is a pre-MS

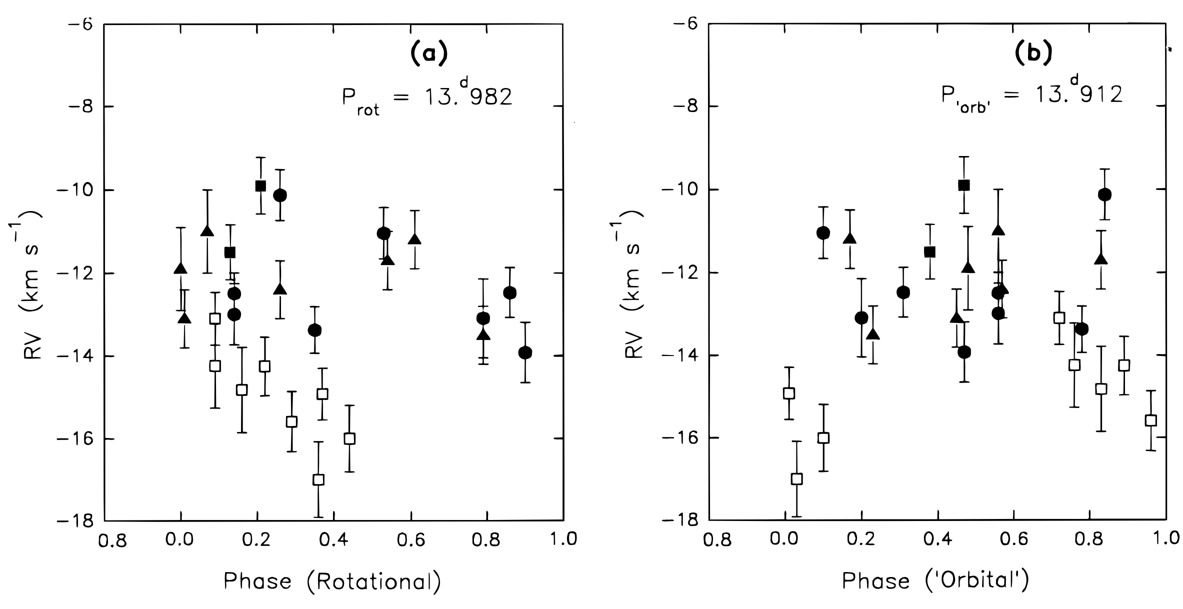


FIG. 8.—All available radial velocities for 1E 1751 + 7046 plotted against: (*a*) the photometric period ($13^{d}.982$); and (*b*) the suggested "orbital" period ($13^{d}.912$), from Jetsu et al. (1992). The radial velocities are coded as follows: (*filled squares*, Silva et al. 1985); (*open squares*, Fleming et al. 1987); (*filled circles*, B. Hrivnak, this paper); (*open triangles*, F. Fekel, this paper). All evidence for an orbital period comes from the Fleming et al. data and does not appear to be confirmed by our 15 new radial velocities.

star can be eliminated because of its large distance above the galactic plane ($z = 160$–$320$ pc), the absence of any surrounding or nearby nebulosity, and its remoteness from any known star-forming region (see also Fleming et al. (1987). In addition, although its Li abundance is significant, it is much less than that of T Tauri stars (see Fig. 2 of Strom et al. 1989). And finally, its $T_{eff}$ and luminosity range put it at or above the theoretical stellar birthline (Palla & Stahler 1990), the locus in the H-R diagram where young objects first become optically visible.

### 4.2. *Post–Main-Sequence Options*

The most difficult properties for any evolutionary scenario to explain are 1E 1751+7046's high rotational velocity and large Li abundance. Mid-G through K single giants are both expected and observed to have rotational velocities $\leq 5$ km s$^{-1}$ (Gray 1989). More rapid rotation, such as 1E 1751+7046's $v \sin i = 23$ km s$^{-1}$, can result from tidal interaction in RS CVn and other interacting binary systems, but in those cases periodic velocity changes clearly reveal a companion. The high Li abundance [$\log \epsilon(\mathrm{Li}) = 1.8$] is difficult to understand since a low-mass star should have depleted its original Li supply by the time it reaches the base of the giant branch, and there are currently no known mechanisms to produce Li in low-mass giants. The scarcity of either or both of these properties in single giants implies that this evolutionary phase is very short-lived, and/or occurs only in stars within a very narrow mass range. Each of the two scenarios below explains most, but not all, of the properties of 1E 1751+7046.

#### 4.2.1. *Coalesced Stars*

Bopp & Stencel (1981) found FK Comae to be an extremely active, extremely rapidly rotating single G giant, and proposed that it evolved from the coalescence of a short-period, contact (W UMa) binary (Webbink 1976).

The apparent progenitors of coalesced stars, the W UMa contact binaries, are OD objects (Baliunas & Guinan 1985; Guinan & Bradstreet 1988), and their frequency, as well as considerations of their evolution, indicate the coalescence is probably inevitable (Guinan & Robinson 1986). If, in fact, stars do coalesce there should be many more in various stages of rotational deceleration than there are spinning at the extreme rate, 150–160 km s$^{-1}$ (Fekel & Balachandran 1993), of FK Com.

As discussed by Guinan & Robinson (1986), FK Com's identification as OD comes chiefly from its relatively high space motion, $S = 80$ km s$^{-1}$, and large $z$-distance ($245 \pm 50$ km s$^{-1}$). Although the high $z$-distance of 1E 1751+7046 suggests OD population, its radial velocity, which is the only known component of its space velocity, is low (Table 1) and consistent with intermediate or young disk, as are its solar-like abundances. The likelihood that 1E 1751+7046 is a coalesced star would increase if it is confirmed as intermediate or OD population. Although there are no published astrometric data for 1E 1751+7046, a parallax and proper motion should become available from *Hipparcos* observations. This (combined with the radial velocity) will at last permit the determination of a space velocity and set some constraints on the star's age and evolutionary stage.

The strongest support for the coalesced binary or spun-down FK Com star hypothesis is the exceptionally high chromospheric (Mg II), TR (C IV), and coronal fluxes, which are similar to those of the most active binaries and to FK Com itself (Figs. 3, 4, 5). While 1E 1751+7046 is spinning more slowly than FK Com (23 km s$^{-1}$ vs. 160 km s$^{-1}$), in a coalesced (or coalescing) star the internal angular-momentum distribution is almost certainly still changing, and high surface fluxes would be expected.

The major problem with this option remains 1E 1751+7046's abnormally high Li abundance. It is not clear why or how Li would be produced during coalescence: any Li created in short-lived nuclear reactions during the interaction of the two stellar cores would be circulated to much hotter regions almost immediately and destroyed. Unfortunately, it is unlikely we will ever determine a Li abundance for FK Com itself because of the extreme rotational broadening of the lines and because any Li line would be weaker in a G2 star (FK Com) than in a K0 star (1E 1751+7046).

#### 4.2.2. *Angular Momentum Transport*

Simon & Drake (1989) first suggested core angular-momentum (AM) transfer as the cause of rapid rotation in a small group of single, moderately rapidly rotating, chromospherically active giants (Fekel et al. 1986; Balona 1987). Fekel & Balachandran (1993) extensively discussed the properties of those stars and argued that such a mechanism was an alternative to coalescence for many rapidly rotating late-type giants. The stellar-evolution models of Pinsonneault et al. (1989), which include rotation, provide a theoretical explanation for the rapid rotation seen in those giants. Their models find that rotational braking on the main sequence leaves the core of the Sun spinning rapidly while the outer convective envelope is spun down. As such a star evolves to the base of the red giant branch, its surface convection zone deepens and high angular momentum from the core may be transferred to the surface. The transfer of angular momentum in such late-type stars creates a dynamo that results in chromospheric activity.

In terms of its rapid rotation, anomalously high Li abundance, and spectral class, 1E 1751+7046 is indistinguishable from the five rapidly rotating, Li-rich, single giants in the Fekel & Balachandran (1993) sample (HD 9746, HD 25893, HD 31993, HD 33798, and HD 203251; their remaining single giants have low, i.e., normal Li). These five proposed AM transfer giants have spectral classes between G8 III and K2 III, 6 km s$^{-1}$ $< v \sin i <$ 40 km s$^{-1}$, $7.5 < P_{rot} < 76$ d (from photometric modulation), and Li abundances at or above the maximum predicted from standard models: $1.4 < \log \epsilon(\mathrm{Li}) < 2.8$ (compare with Table 1). Even an OD space motion for 1E 1751+7046 would not weaken these similarities since one of the five AM transfer giants (HD 33798) is OD.

Although the Pinsonneault et al. models can explain the rapid rotation, neither their models nor any others predict enhanced Li in first-ascent and clump giants. The only process currently known for manufacturing Li in post-MS evolution is the $^{7}$Be transport mechanism (Cameron & Fowler 1971), which, in more massive second-ascent asymptotic giant branch stars, is believed to operate at the bottom of the convective envelope (Sackman, Smith, & Despain 1974). If this mechanism also operates in less massive first-ascent giants, it would have to take place much closer to the core than in more massive stars in order to reach the temperatures necessary to create $^{7}$Be (which decays into $^{7}$Li). Thus Fekel & Balachandran (1993) argue that the transport of Li-rich material into the outer envelope of the star could well accompany the core AM transfer predicted by the Pinsonneault et al. models. In fact, the low ($7 < {}^{12}C/{}^{13}C < 25$) values measured for a few single Li-rich giants are evidence that the dredge-up of nuclear processed material does occur in low-mass giants (Brown et al. 1989). Therefore, this scenario could apply to 1E 1751 + 7046 as well. Unfortunately, the large rotational broadening of 1E 1751 + 7046 also makes a measurement of the ${}^{12}C/{}^{13}C$ ratio extremely difficult, if not impossible.

The only major difference between the five rapidly rotating, Li-rich, single giants and 1E 1751 + 7046 is the higher activity level of 1E 1751 + 7046. The X-ray flux of 1E 1751 + 7046 is about two orders of magnitude higher than that of HD 31993, the only one of the five AM transfer giants having a measured X-ray flux (Fig. 5). All five AM transfer giants have C IV values that lie a factor of a few lower than 1E 1751 + 7046 (Fig. 4).

Although there are no Mg II fluxes for any of the five single giants mentioned above, high-resolution Ca II H + K and H$\alpha$ profiles show that chromspheric activity, too, is more enhanced in 1E 1751 + 7046. The equivalent width (EW) of the Ca H + K emission is higher in 1E 1751 + 7046 (Fig. 1) than in the four AM transfer giants for which observations exist (Strassmeier et al. 1990). For H$\alpha$, four of the five Li-rich, rapidly rotating, single giants show deep H$\alpha$ absorption; the fifth (HD 9746) is about 40% filled in (Table 6*a* in Strassmeier et al. 1990). In contrast, the H$\alpha$ line for 1E 1751 + 7046 in similar high-resolution spectra is about 70% filled in (Fleming et al. 1987).

1E 1751 + 7046's $v \sin i$ value of 23 km s$^{-1}$ and its lower limit of $i$ of 30° suggests that its true rotational velocity is less than or comparable to the fastest rotator among the five AM transfer giants, HD 203251 ($v \sin i = 40$ km s$^{-1}$). Because of the close link between rotation and activity, the high surface fluxes would seem to imply a significantly different internal angular momentum structure for 1E 1751 + 7046, which, in turn, brings into question its fundamental similarity to these stars.

## 5. SUMMARY

Two post-MS scenarios may explain the revised properties of 1E 1751 + 7046.

First, the Fleming et al. (1987) suggestion that it is a spun-down coalesced binary survives. Properties consistent with this scenario include: (1) a large $z$-distance similar to that of FK Com; (2) rapid rotation, although not nearly as rapid as the extreme rotation of FKCom; (3) near saturation coronal and TR fluxes.

To support this scenario a large space velocity also is required. For 1E 1751 + 7046 the low and rather unspectacular radial velocity of $-12.3$ km s$^{-1}$ is, by itself, inconclusive without a measured proper motion, which should shortly be available from *Hipparcos*. Likewise, the approximately solar abundances of 1E 1751 + 7046 are not necessarily inconsistent with an OD coalesced star, since the wide abundance range of their likely progenitors, the W UMa stars, includes solar abundance (Rucinski 1983). Most damaging to this model is the unusually large Li abundance of $\log \epsilon(\mathrm{Li}) = 1.8$.

The second scenario proposes that the rapid surface rotation and consequent high atmospheric activity levels of 1E 1751 + 7046 result from angular momentum transferred from the core to the surface. Properties consistent with this scenario are: (1) the spectral class and rotation rate of 1E 1751 + 7046 match the five single, AM transfer giants of Fekel & Balachandran (1993); (2) both OD and YD stars are represented in this sample, so the final space velocity and abundances of 1E 1751 + 7046 are not critical; (3) The Li abundance of 1E 1751 + 7046 matches that of the five AM transfer giants.

Of greatest concern to this model are the high flux levels of the upper atmosphere, which more closely match those of FK Com.

While the high Li abundance of 1E 1751 + 7046 is a problem for either scenario, it seems at least possible that the ${}^{7}$Be transport mechanism could produce some Li in low-mass giants. This Li ultimately would reach the surface during an AM material-transfer phase before being destroyed. Low ${}^{12}C/{}^{13}C$ ratios for a few single, Li-rich giants (Brown et al. 1989) are evidence that nuclear-processed material does reach the surface in first-ascent giants. Lithium seems, at this point, to be a more serious problem for the coalesced binary hypothesis, since any Li created in nuclear reactions during the merger of two cores would appear to be destroyed instantly during rapid mixing into hotter regions. We hope that stars such as 1E 1751 + 7046 will spur theoretical advances on post-MS Li production in low-mass giants.

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