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HIGH-LATITUDE SPOT AND PLAGE ACTIVITY ON THE RAPIDLY ROTATING M DWARF STAR GLIESE 890

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ABSTRACT

The star Gliese 890 (HK Aqr) is a single M dwarf of the BY Draconis (dMe) type which is distinguished by having the shortest known period of rotation (10 hr 30 minutes) among the field stars of its type. We present the results of simultaneous time-resolved observations of GL 890 in broad-band (*V*) photometry, and in Hα and near-ultraviolet (Mg II *hk*) spectroscopy. Additionally, we present broad-band photometry extending over more than 1 yr (∼1000 rotation cycles).

Our continuum light curves exhibit modulations which are characteristic of the presence of localized dark spot regions, and our spectra exhibit corresponding modulations of the intensity of Hα emission, with the latter being substantially in phase with the former. Secular changes in the continuum light curve lead to the conclusion that the geometry of the spots changes appreciably over time scales which are of the order of 60 rotation periods.

We find that the overall chromospheric activity, judged by the excess luminosity in Hα and Mg II *hk*, is not significantly greater than that which is found in similar stars which rotate much more slowly.

Our analysis of the differential radial velocities of the Hα emission profile suggests that the principal active region present on the visible disk of the star during our observations was at a remarkably high latitude (in excess of 60°) compared to the occurrence of such regions on the Sun. This raises the question of whether the extremely rapid angular velocity (60 times solar) confines such activity to the polar latitudes of the star or merely permits it to migrate to such latitudes, with our observations coinciding with just that phase of the activity cycle.

Subject headings: stars: chromospheres — stars: individual (Gliese 890) — stars: late-type — stars: rotation — ultraviolet: spectra

I. INTRODUCTION

The stars with the least mass among those of the galactic disk population, the M dwarfs, having the longest main-sequence lifetimes, would naturally be thought to consist of the oldest members of that population. However, it has long been known from kinematical studies, e.g., Vyssotsky and Dyer (1957), that a subset of relatively younger objects with similar masses cohabit the solar neighborhood. These younger members of the M dwarf population invariably exhibit, to greater or lesser degree, evidence for activity in their chromospheric and coronal layers which are recognized (by analogy with solar activities) as the manifestation of strong, localized magnetic regions. Skumanich (1972) established the quantitative connection of one of these activity indicators, Ca II HK, with rotation, and demonstrated that a common decay law held, thus establishing both as clocks for the main-sequence stage of low-mass stars. Given the inferred spread of ages of the low-mass stars in the solar neighborhood, and the rotation-activity decay law, the demonstration of short period photometric modulation among dMe stars by Bopp and Espenak (1977) completed the picture and provided credibility for an emerging viewpoint. With the exception of GL 890, there are 10 other dMe stars which are known to be single and to exhibit photometric rotational modulation, and all have known periods. The mean period of rotation for that small sample is 2.98 days, with a dispersion of 0.94 days. The shortest period in that group (GL 875.1) is 1.6 days, and the longest period (GL 803) is 4.85 days. With its exceptionally short rotation period of 0.4307 days (10 hr 20 minutes), GL 890 stands out among the field dMe stars (see the review by Stauffer and Hartmann 1986). The studies published by van Leeuwen and Alphenaar (1982) and by Stauffer (1984) reveal that dMe stars with rotation periods as short, or shorter, than that of GL 890 exist in the young Pleiades cluster. It appears that the relationship of the young field dMe stars and the Pleiades might bear reexamination in view of our discovery of the short period of rotation of GL 890.

In this study, the astrophysical consequences of such extremely rapid rotation (nearly 60 times the solar rate) of a convective envelope is the principal concern. While such rota-

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tion rates are not unprecedented in low-mass stars, they typically occur in tidally locked binary systems where the strong tidal couple may affect internal flow structures, and consequently they may alter the surface activity which results from the coupling of rotation with convection. This star presents a unique opportunity to examine the coupling of rapid rotation with convection in the absence of the potentially complicating effects of external tidal coupling. Similar stars in the Pleiades cluster are too faint for existing technology to permit a detailed scrutiny of their surface activity.

A thorough study of GL 890, including broad-band photometry, low resolution spectroscopy, and detection of flare activity, has been published by Pettersen *et al.* (1987). Our photometric observations both predate and postdate theirs, revealing significant alterations of the surface configurations of dark spots; also our high-resolution and time-resolved spectroscopy of Hα and of the Mg II *hk* lines permit us to infer the probable locations of bright active regions. In § III, we go to some length to give a complete discussion of all of the arguments which, collectively, lead us to the conclusion that the magnetic activity signatures which we have observed on GL 890 (i.e., dark spots and emissive plages) are at very high latitude on the stellar disk. Although various investigators have made similar assertions about several active stars (references to be cited in § III), it remains controversial as to whether or not magnetic activity near stellar rotation poles is a reality. There are many objections to such a contention, making the issue one which must be treated with care. Not the least objection is that such activity is never observed at high latitude on the Sun, which is the only star upon which magnetic activity has been directly observed and mapped. Another objection stems from the fact that unresolved stellar disks present us with ambiguous situations; e.g., many small spots distributed appropriately in longitude, in equatorial latitudes, can mimic a few larger spots distributed differently but at high latitude. A complete discussion of all the evidence is therefore necessary to make a compelling case for stellar activity at high latitudes.

II. OBSERVATIONS

a) Broad-Band Photometry

All the photometric observations reported in this paper were made at the Mount Laguna Observatory, using the 1.0 m telescope which is operated jointly by the University of Illinois and San Diego State University. Most of the observations were made using the *V* filter of the *UBV* system, but some were made with the *y* filter of the *uvby* system. Light curves in each of the filters are plotted separately, and all of the data are presented in Table 5, which appears in the Appendix. Analysis of these observations is complicated by intrinsic changes in morphology of the light curve, presumably attributable to growth and decay of spot regions on a time scale of a month or so. Observations extending over three or four days (∼10 cycles) appear to superpose in a reasonable fashion upon a phase scale computed from our best estimate for the period of rotation. Observations separated by more than a few months usually defy such assembly, requiring some adjustment of the period and epoch coefficients and reducing confidence in the plotted curve as being representative of a single light curve obtained over a few cycles. The morphology change from a single to a double sinusoid and the large gaps in our sampling windows greatly complicate the derivation of a unique period from the usual procedures of frequency analysis. Nevertheless, we have derived an ephemeris which appears to represent all of our data, and so all of the tabulated and plotted phases for the photometric data are computed from

$$\mathrm{JD} = 2{,}445{,}578.980 + 0.4307E\,. \qquad (1)$$

Our period differs slightly from the value (0.4312 days) derived by Pettersen *et al.* (1987), which is not surprising in view of the complexity of the variations exhibited by this star.

The stated epoch is based on our determination of the time of maximum brightness in the first light curve and has no significance beyond that. The first light curve, shown in Figure 1, consists of the combined observations from 1983 September 3, 4, 5 (UT dates) and is a revised version of the discovery light curve originally published by Young *et al.* (1984). Later analysis of additional data revealed that the original comparison star which was used to reduce those observations was slightly variable, and that it was possible to correct the reductions by means of a check star which was observed during the first run and more intensely during succeeding runs. The adopted comparison star to which all of the differential magnitudes now refer is SAO 165501, and the data are listed on the instrumental system.

Pettersen *et al.* (1987) give magnitudes and colors for GL 890 which have been transformed to the standard system, and it is apparent that agreement to better than 0.1 m in the *V* band is not forthcoming. Their published light curve, observed in 1983 October and December, is substantially in agreement with our 1983 September curve, shown in Figure 1. However, they find a peak-to-peak amplitude of 0.12 m, while we find 0.096 m. This is not surprising in view of what we find about the variability of the surface activity. In general, our rms error for differential magnitudes is 0.005 m, so that local minima in the light curve that are as small as 0.02 m represent a 3 σ detection.

Figure 2 is a second season light curve obtained in the *y* filter on the nights of 1984 August 2, 3, 4. Major changes have occurred over the interval of nearly 1 yr. The peak-to-peak amplitude has dropped to about 0.03 m, and the light curve displays two minima and two maxima which are reasonably

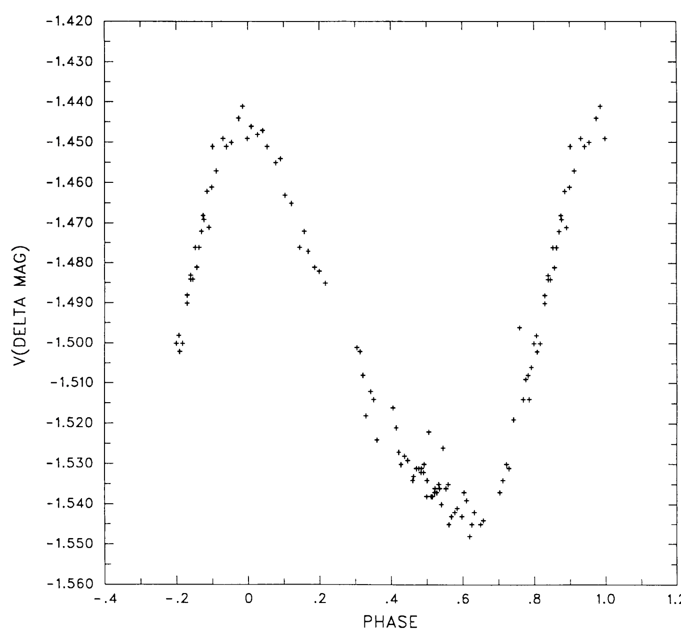

FIG. 1.—Observed light curve of GLS 890 in the *V* band on the nights of 1983 September 3, 4, and 5 (UT). Phase is from eq. [1].

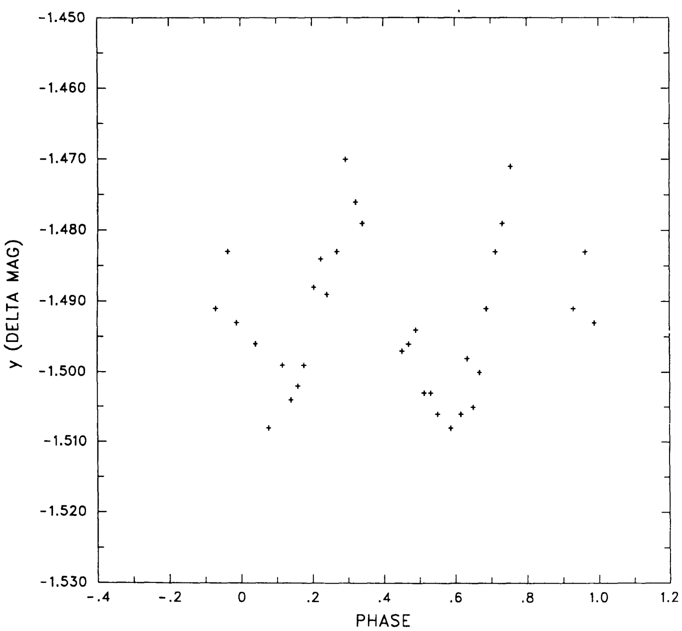

FIG. 2.—Observed light curve of GLS 890 in the y band on the nights of 1984 August 2, 3, and 4 (UT).

symmetrical in phase, suggesting two major spot groups separated by about 180° in longitude on the star. If this had been the discovery light curve, it is virtually certain that we would have derived an incorrect period of about one-half of the currently quoted value. The arguments which support our value as the correct one are given by Pettersen *et al.* (1987), citing the consistency which this period brings to the observed rotational velocity inferred from the broadening of the photospheric absorption lines, and a reasonable radius for an M dwarf star. We shall produce arguments below which support and extend theirs, showing that the axis of rotation of the star, while not necessarily in the plane of the sky, is inclined considerably to our line of sight.

Figure 3*a* is the third epoch light curve derived from our observations on the nights of 1984 October 11 and 13 (*plus signs*) and November 12 (*filled dots*) assembled on a common phase scale. Although different in detail from the previous light curve two months earlier, the same two major spot groupings seem to dominate the surface.

One property which is common to all the visual light-curves is that there is no substantial interval of essentially constant light as might be expected if a single large spot (or concentrated group of spots) were to cross the visible disk between its limb-crossing episodes. Taken by itself, this information is ambiguous in its interpretation, because it could be reproduced by many combinations of spot temperatures, filling factors, and longitude distributions. Since the peak-to-peak amplitude of the light curve has not yet been known to exceed 12% and is often as small as 3%, it is not likely that the filling factors for the spot regions are much larger than those values unless these are exceptionally warm spots. Therefore, one natural and simple interpretation would place the spot regions (one in 1984 September, and two in 1984 October) at very high latitude on the star, so that a relatively small filling factor could occupy a large range of longitudes, such that one spot region might begin rising before the other has completed setting, even though their centers are separated by 180° in longitude. Since solar activity remains the paradigm for the interpretation of stellar activity, and high-latitude spot activity does not occur on the Sun, it is understandable that such an interpretation is not greeted with enthusiasm. Nevertheless, the analysis of our Hα observations (§ III) is strongly indicative of high-latitude activity, so that the complete picture leads to a more compelling argument that all of the obvious manifestations of magnetic activity on GL 890 are at high latitudes.

Still another characteristic of the light curves which is worthy of some discussion is a particular asymmetry which is best seen in Figures 1 and 3*a*. The increase to maximum light is distinctly shorter than the decrease to minimum light. In a later section, we calculate the effect upon the time scale of both rising and setting phases of various source latitudes over the limb of a star whose axis of rotation is inclined considerably to our line of sight. Suffice it now to state that the two poles (i.e., the visible and the unseen) behave in an inverted sense with respect to this issue. For example, if a spot region is near the *unseen pole*, its lowest latitude extent would be required (by the observations) to be ahead in longitude (i.e., in the prograde sense) of the highest latitude extent. Such a configuration would cause both the high-latitude and low-latitude regions to set at more nearly the same time, thereby generating a steep gradient in the increasing brightness of the visible stellar disk. At rising, the converse would be true, with the low-latitude region rising well before the high-latitude region, thereby extending the duration over which the visible disk darkens. At the *visible pole*, it would be necessary for the lower latitude extent of the spot to be retarded in longitude (i.e., in the retrograde sense) in order to achieve the same kind of observed asymmetry in the light curve. The photometry alone does not permit a distinction to be made as to which pole contains the spots; they could also be at both poles. The detailed analysis of the Hα spectroscopy, however, argues (though not definitively) for the bright regions being near the unseen pole. If that is where the spots are also, then the previous argument hints at a

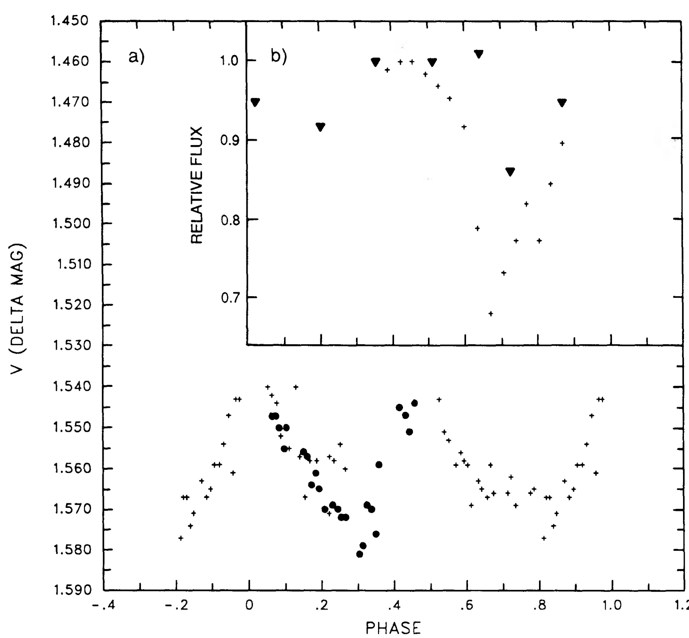

FIG. 3.—(*a*) Observed light curve of GLS 890 in the V band on the nights of 1984 October 11 and 13 (*plus symbols*), and November 12 (*filled circles*); dates are UT. (*b*) Relative chromospheric emission flux for GLS 890 in Hα (*plus signs*) and in Mg II h and k (*inverted triangles*) vs. phase. The Hα data are excess equivalent widths above the zero point star GLS 412.

differential rotation which, at least at high latitude, accelerates toward the equator in the same manner as such motion occurs on the Sun.

b) Hα *Spectroscopy*

The spectroscopic observations were scheduled to be simultaneous with the broad-band photometry and the Mg II *hk* spectroscopy on the nights of 1984 October 11, 12, and 13, using the 2.1 m telescope and its coudé spectrograph at the Kitt Peak National Observatory. The first night was lost to an unexpected system failure, and the second night was overcast. Observations were made on the third night, but only from 2:00 UT until 7:00 UT, when high humidity terminated further observing. Because of these circumstances, only 15 sequential spectra were obtained, over a range of phases just under one-half of a complete rotation cycle, between phases 0.4 and 0.9 as given by our ephemeris (eq. [1]). This abbreviated span partially contributes to the ambiguities encountered in the interpretation of the measurements.

The spectra were recorded on a TI-3 CCD with 800 pixels, giving a 2 pixel resolution of 440 mÅ and extending over a band of 177 Å centered on Hα. Integrations of 1200 s were required to maintain an acceptable signal-to-noise ratio of no less than 50, yielding a resolution of 0.03 in phase.

The spectra were convolved with a low-pass apodizing filter to attenuate the high frequency noise, and fitted with a pseudo-continuum to achieve scale normalization. Analysis of the absorption line bisectors and successive spectrum subtractions showed no detectable variation of the radial velocity of GL 890 as judged by the 10 photospheric absorption lines which could be readily identified. Since one-half of the photometric period was observed, the apparent constancy of the photospheric radial velocity constitutes a strong argument that the star is not a member of a close binary. All 15 spectra were then signal averaged to form one mean photospheric spectrum whose geocentric radial velocity was measured, relative to the comparison lines, using six of the 10 identified absorption lines. From that result (+25.7 km s^{-1}), a rest position for Hα (relative to the photospheric lines) was computed, and all quoted values for the radial velocity of Hα in this paper are relative to that position and are thus referred to as differential radial velocities. It should also be noted that when the appropriate heliocentric correction is applied to the radial velocity computed from the photospheric absorption lines, the result for GL 890 is +7.0 km s^{-1}, which is in excellent agreement with the value (+8.5 km s^{-1}) which was found by Pettersen *et al.* (1987).

Table 1 presents the results of the reduction and measurement of each of the Hα spectrograms. Column (1) lists the UT of the middle of the integration. The next column lists the phase for each time computed from the ephemeris given by equation (1). This phase is used to permit a direct comparison of these Hα values with both the broad-band photometry and the Mg II *hk* spectroscopy. Column (3) lists the differential radial velocity, while column (4) lists the equivalent widths of the emission feature above the local continuum. Column (5) contains the relative intensity of the peak of the Hα profile.

In order to compare the Hα data with those of Mg II *hk*, which represents the excess chromospheric luminosity, we subtract the equivalent width of Hα in an inactive star of approximately the same color, GL 412, from that of GL 890 and use this *excess* as a measure of the chromospheric Hα luminosity. We use the value of 0.40 Å for the equivalent width of Hα in the spectrum of GL 412 (Young, Skumanich, and Harlan 1984).

TABLE 1

SPECTROSCOPIC Hα DATA

Mid-Exposure (UT) (1)	Phase (eq. [1]) (2)	V_r (km s^{-1}) (3)	EW (Å) (4)	Peak Intensity (5)
2:10	0.390	−6.8	1.94	1.66
2:32	0.426	−5.8	1.97	1.67
2:52	0.458	−5.6	1.97	1.67
3:15	0.495	−5.0	1.92	1.66
3:36	0.529	−3.9	1.88	1.63
3:56	0.561	−0.9	1.84	1.58
4:20	0.600	+3.8	1.74	1.56
4:41	0.634	+12.4	1.44	1.45
5:03	0.669	−1.9	1.22	1.33
5:25	0.705	−13.4	1.32	1.41
5:47	0.740	−6.2	1.40	1.43
6:04	0.768	−3.5	1.51	1.42
6:26	0.803	−2.8	1.40	1.38
6:46	0.835	−9.5	1.57	1.45
7:06	0.868	−10.1	1.69	1.56

Figure 3*b* is a plot of the relative fluxes of Hα and Mg II *hk*, normalized to unity at their maxima, on the same phase scale as the simultaneous photometric observations.

Figure 4 shows four selected spectra in the region of the Hα emission feature, all normalized to a continuum level of 10^4. It is apparent that the peak intensity of the Hα profile drops by about 50% (the reduction is only 30% when expressed as an excess equivalent width relative to the zero point star), and that the bisector of these profiles differs in a systematic manner. What is not apparent is that *none* of the profiles are actually symmetrical as judged by their bisectors. That asymmetry varies in a complicated manner, which may be the result of each profile being a convolution of profiles from two or more sources whose aspect varies with phase. Neither our temporal nor our wavelength resolution justifies any attempt to sort out such complexity, and, without further observational constraints, we would be speculating as to the number and con-

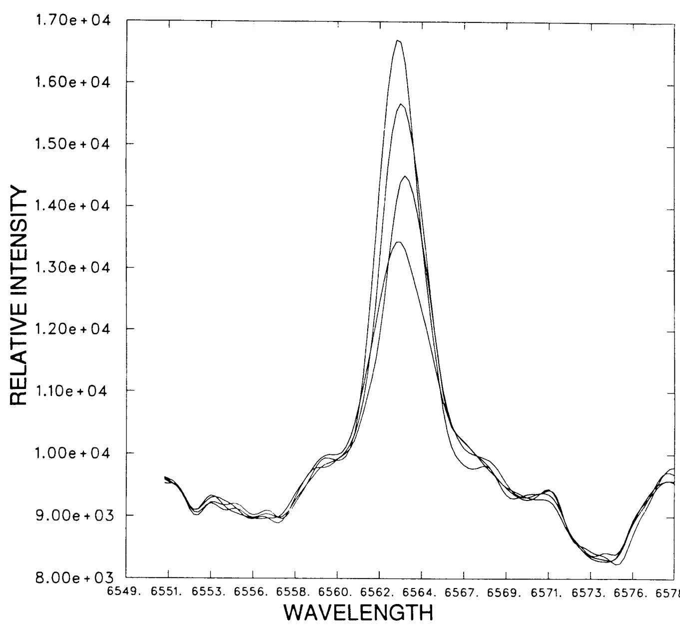

FIG. 4.—Superposition of four spectra of GLS 890 in the region of Hα, observed on the night of 1984 October 13 (UT). The phases illustrated (in order of decreasing peak intensity) are 0.40, 0.60, 0.63, and 0.67.

figuration of such component sources. Therefore, we have assumed that the Hα profile is dominated, over a restricted range of phases, by one coherent emissive region (plage) which crosses the visible disk as the star rotates. We have used the bisector of the upper one-third of the Hα profile to evaluate the differential radial velocity of such a region, which is induced by the rotation of the star. There are indications in the radial velocities that at least two distinct plage regions exist which are separable in velocity-space, and for that reason the peak intensity has served as a useful indicator of the status of the dominant region as the rotation progresses.

The finite size of any emissive plage region decrees that our measured values of differential radial velocity must be some kind of average over the plage. The observed fact that the peak intensity (and the equivalent width) of Hα decreases synchronously as the visual light curve decreases indicates that the primary plage is at a considerably different longitude from that of the spot(s). The erratic behavior of the differential radial velocity after phase 0.7 (minimum continuum brightness) is suggestive of a new plage rising, but the termination of our observations precludes a definitive statement.

The presence of other emissive sources or of a global (i.e., uniform) contribution to Hα as well would cause our measurement procedure to systematically underestimate the correct differential radial velocity of any single source region by an amount which is dependent upon the relative contribution to the observed profile by each of the components. Failure of the Hα emission to ever vanish entirely argues for more than a single source, but our (restricted) set of observations does not permit us to infer how many sources may be present, and we cannot rule out a global contribution as well.

c) *IUE Observations*

GL 890 was monitored with the instrumentation on board the *IUE* satellite during both the US 1 and US 2 shifts on each of two successive observing days between 1984 October 11 and 13. A total of 17 spectra were obtained in the course of the observing run, 15 with the long-wavelength prime (LWP, 1910–3300 A) camera and two with the short-wavelength prime (SWP, 1150–1975 Å) camera. All exposures were taken through the large (10″ × 20″) aperture at low dispersion (spectral resolution 6 Å). The data so acquired were subsequently analyzed at the Regional Data Analysis Facility at the University of Colorado using the standard reduction programs available there. After removing all the obvious particle "hits" and reseau marks, the absolutely calibrated spectra were smoothed with a five-point running boxcar average, and integrated emission-line fluxes were measured. We estimate that the derived line fluxes are accurate to about 10%.

Of the 15 LWP spectra, four were unacceptably noisy due to either underexposure or the effects of the high particle background which prevailed during the latter parts of both US 2 shifts. Information concerning the remaining 11 exposures is listed in Table 2. In addition to giving the date, starting time, and duration of a given observation, we have also tabulated the observed Mg II *h* (2803 Å) and *k* (2796 Å) line flux at Earth, and the phase at the beginning and end of each exposure as determined from the ephemeris given by equation (1). A portion of each of two representative long-wavelength spectra are shown in Figure 5. These spectra bear strong morphological similarities to those of other dMe stars (see, e.g., Linsky *et al.* 1982). Particularly noticeable features in the spectra include the *h* and *k* lines of Mg II which, at 6 Å spectral resolution,

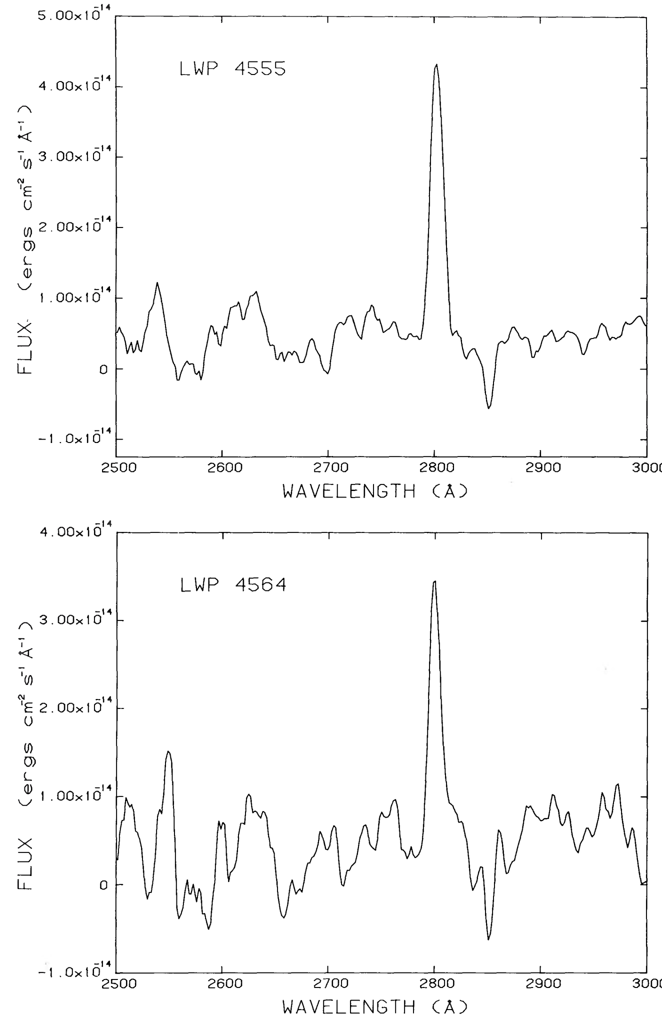

FIG. 5.—Two representative spectra of GLS 890 in the region of the Mg II *h* and *k* lines, observed with the *IUE* on 1984 October 12 (LWP 4555; phase 0.50) and 13 (LWP 4564; phase 0.72); dates are UT.

appear as a single, blended emission peak at 2800 Å and the Mg I absorption feature at 2852 Å. Most of the prominent features between about 2600 and 2800 Å are probably due to emission in several Fe II and Al II multiplets, as identified in the spectra of other cool dwarf stars by Linsky *et al.* (1982). The mean phase $\bar{\phi}$ ($[\phi_{\rm start} + \phi_{\rm stop}]/2$) for the image LWP 4555 is 0.51, while for the LWP 4564, it is 0.72. As is apparent from Figure 5, the intensity at the peak of the Mg II blend in LWP 4555 is approximately 20% greater than that in LWP 4564. The integrated Mg II fluxes appropriate to these exposures are the highest and lowest such values obtained during the observing run, respectively (see Table 2).

To facilitate a more detailed investigation of the way in which the level of emission varies with rotational phase, the observational data listed in Table 2 were further reduced according to the following prescription. As is evident from the tabulation, exposures 4565, 4561, 4562, and 4563 (all obtained during the second observing day) cover virtually the same phase intervals as the first day exposures 4552, 4553, 4554, and 4555, respectively. Inspection of the Mg II *hk* fluxes for each of these exposures further reveals that the fluxes obtained during the first observing day are consistently larger than those

TABLE 2

IUE OBSERVATIONS OF GLIESE 890

IUE Exposure Number (LWP)	Date[a] (1984)	Start Time (UT)	Exposure Time (minutes)	Phase Start	Phase Stop	Mg II Flux at Earth (10^{-13} ergs cm^{-2} s^{-1})
4552....................	Oct 11	23:29:46	60	0.81	0.91	6.4
4553....................	Oct 12	03:12:40	60	0.17	0.27	6.1
4554....................	Oct 12	04:48:23	50	0.32	0.40	6.7
4555....................	Oct 12	06:12:05	60	0.46	0.55	6.8
4556....................	Oct 12	07:46:47	40	0.61	0.68	6.8
4560....................	Oct 12	21:53:00	60	0.98	0.07	5.8
4561....................	Oct 12	23:35:19	60	0.14	0.24	5.7
4562....................	Oct 13	01:17:40	60	0.31	0.40	6.3
4563....................	Oct 13	03:00:55	60	0.47	0.57	6.2
4564....................	Oct 13	05:12:45	50	0.68	0.77	5.2
4565....................	Oct 13	06:44:12	60	0.83	0.93	5.8

[a] 1984 October 11, 00:00:00 UT = JD 2,445,984.5 = phase 0.54.

obtained at the same phase on the second day; the average value of this flux excess is

$$\Delta F = 0.5 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} . \quad (2)$$

Because the flux discrepancy between pairs of exposures with nearly the same phase is within the estimated error of an individual flux measurement, the fluxes and mean phases of each such image pair were averaged together. The remaining three LWP exposures (4556, 4560, 4564) listed in Table 2 are not redundant in phase. A pseudoaverage flux for each of these exposures was constructed by subtracting $\Delta F/2$ from the one obtained on the first day and by adding $\Delta F/2$ to the two obtained on the second day. The average flux values obtained using the procedure described above were normalized and plotted against the mean phase; the results are depicted in Figure 3*b*.

Note that the variation with phase displayed by the observed Mg II *hk* fluxes is *qualitatively* similar to the behavior exhibited by both the Hα fluxes and the visual light curve. However, given that the estimated accuracy of any Mg II flux measurement is only about 10%, the sharp decline of Mg II with its subsequent rise and local minimum near phase 0.7 *may not* be significant. If it is real, however, this behavior is consistent with the solar spot paradigm, according to which the chromospheric emission of Hα and of Mg II *hk* is weakest directly over the spot and should weaken synchronously with the minimum in the visual light. Insofar as there is overlap in the phase coverage between the Mg II observations and the (ground-based) Hα observations, this behavior is essentially common to both. Our observations suggest that the Mg II and Hα bright plage regions are strongly correlated spatially and are separated from the darker spot regions.

As noted above, in addition to the long-wavelength spectra, two low-dispersion SWP exposures (SWP 24160 and 24167) were taken during the observing run, each of length 150 minutes. No discernible emission features are present in either of these spectra. We estimate the integrated noise level at the wavelength of the C IV resonance doublet (1549 Å) in these spectra to be about 3.3×10^{-14} ergs cm^{-2} s^{-1}, yielding an approximate 3 σ upper limit to the C IV line flux of 10^{-13} ergs cm^{-2} s^{-1}. To check this result, we note that the data set of Linsky *et al.* (1982) includes a number of dMe and dKe stars for which both Mg II and C IV emission have been detected. A least-squares fit to the measured fluxes at the Earth yields the relation

$$\log (f_{\rm C\,IV}/f_{\rm bol}) = 0.57 \log (f_{\rm Mg\,II}/f_{\rm bol}) - 2.48 , \quad (3)$$

where $f_{\rm bol} = \text{dex}(-0.4[m_{\rm bol} + 11.42])$ is the apparent bolometric flux. A value of $m_{\rm bol}$ for GL 890 can be obtained as follows. B. R. Pettersen (private communication) determined the $(R-I)$ color index for this star to be 0.9. Using the relation between the bolometric correction (BC) and the $(R-I)$ color derived for cool dwarf stars by Pettersen (1982), we obtain BC = −1.04, from which it follows that $m_{\rm bol} = 9.56$ and $f_{\rm bol} = 4.1 \times 10^{-9}$ ergs cm^{-2} s^{-1}, assuming $m_v = 10.6$. From Table 2, the average observed Mg II *hk* flux for GL 890 is $f_{\rm Mg\,II} = 6.2 \times 10^{-13}$ ergs cm^{-2} s^{-1}, so that $f_{\rm Mg\,II}/f_{\rm bol} = 1.5 \times 10^{-4}$. With this result, the relation given above yields $f_{\rm C\,IV}/f_{\rm bol} = 2.2 \times 10^{-5}$ or $f_{\rm C\,IV} = 9.0 \times 10^{-14}$ ergs cm^{-2} s^{-1}, a value consistent with the observationally determined upper limit.

III. ANALYSIS

a) Hα *Spectroscopy*

Our observation that minimum chromospheric luminosity occurs synchronously with minimum photospheric luminosity is in contradiction to recent studies which indicate an anticorrelation of such activity tracers in cool stars (for a review see Baliunas 1987). Examples are the active component stars of II Peg (Vogt 1981), λ Andromeda (Baliunas and Dupree 1982), and δ Cor Bor (Baliunas 1987). It is important to note that all of the aforementioned stars are evolved subgiants and that, except for δ Cor Bor, they are members of tidally coupled (RS CVn) binary systems. The observed anticorrelation in those stars has been interpreted as a congruence of emission plage and dark spot regions with the plage chromosphere contribution exceeding the spot chromosphere contribution. Our observations demonstrate that this is not the case for GL 890.

On the Sun, mature active regions consist of dark spots *preceding* bright plage regions (refer to Bray and Loughhead 1979; Meyer, Schmidt, and Weiss 1977). Our observation of synchronism of *brightest* emissivity of the chromospheric emission with *maximum* photospheric output (i.e., a nearly immaculate stellar disk) implies a longitude difference between the dark spot region and the bright plage region which is of the order of 90°. The particular plage which our observations encompass appears to be *leading* the dark spot, but it is quite possible that the plage is trailing the other spot and that there is yet another plage trailing the spot which is on the visible disk at rotation phase 0.7. The incompleteness of our phase coverage of Hα prevents such a determination from being made. The solar paradigm can be preserved for GL 890 only if the active regions on GL 890 are confined to high (i.e., near-polar) latitudes where a difference of 90° in longitude between the dark spot and the bright plage would not oblige the spot and the plage regions to be separated by an appreciable fraction of the stellar circumference. In a recent analysis of the rapidly rotating K dwarf star HD 36705, (AB Dor) Vilhu, Gustafsson, and Edvardsson (1987) concluded that precisely such a configuration was implied by their observations, with the bright Hα plage region *leading* (sic) the dark spot by about 90° in longitude, and with both located at high stellar latitude. Our finding, therefore, is not without precedent in another star. It seems more than coincidental that two stars which rotate with comparable and exceptionally rapid angular rates display such similar geometry with respect to their magnetically active regions; i.e., both confined to the polar latitudes and both exhibiting a 90° difference in longitude between the plage and the spot. Since our light curve for GL 890 shows that two spot groups are present on the disk, separated in longitude by about 180°, it is not possible to state unambiguously whether the observed plage region is leading one group or trailing the other. The Sun, however, provides us with a basis for preferring the latter interpretation over the former.

The previous argument constitutes only circumstantial evidence for a high-latitude location of the observed active region on GL 890. Figure 6 is a plot of the measured differential radial velocities (*filled circles*) with phase. For comparison, the peak Hα intensity is also plotted on the same phase scale (*vertical bars*). The systematic progression of the first eight values suggests a plage region which was moving across the visible stellar disk when the observing sequence began, transited the central stellar meridian sometime during the observation sequence, and vanished over the receding limb sometime between the eighth and ninth observations. The tenth observation (phase 0.70) suggests a second region rising over the approaching limb, while the fourteenth and fifteenth (phase 0.85) might imply yet a third region rising while the second one continues transiting the visible disk. The lack of further observations renders any further discussion of the putative second and third regions futile. Our analysis, therefore, is confined to the first region, whose transit across the receding (setting) limb appears to be well established by radial velocity.

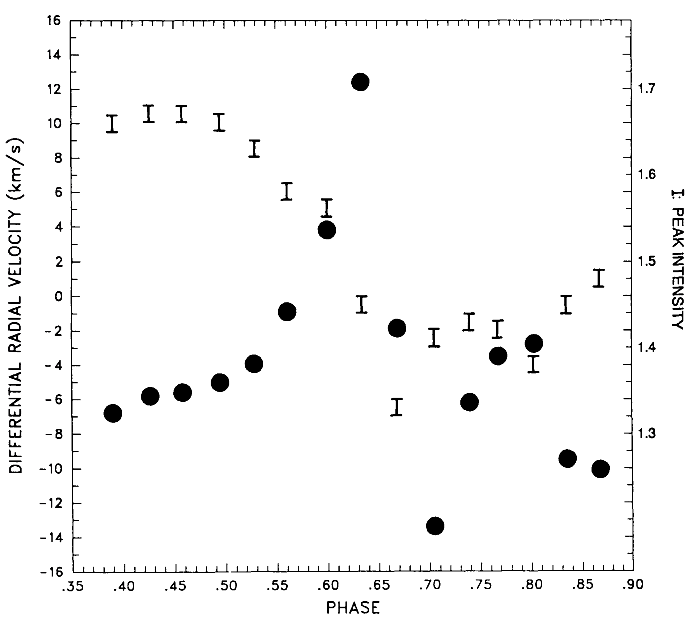

FIG. 6.—Differential radial velocities (*filled circles*) and peak intensities (*vertical bars*) of the Hα profiles of GLS 890 as a function of phase.

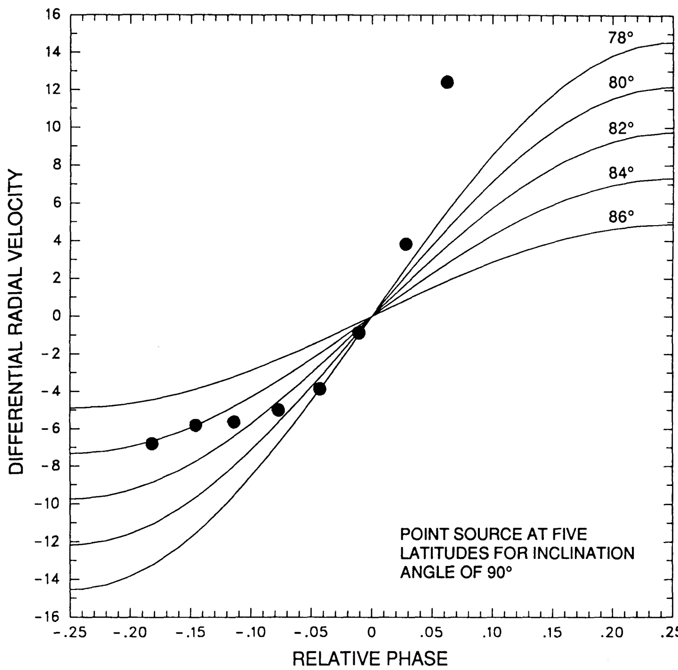

FIG. 7.—Predicted differential radial velocities for point sources at five latitudes compared with the first eight observed values, shifted to have zero phase at zero velocity crossing.

In Figure 7, we have plotted a series of sine curves which depict the radial velocity of point sources crossing the stellar disk at the inscribed latitudes, assuming an equatorial velocity of 70 km s^{-1} and an axial inclination of 90°. For the purpose of this discussion, we take the transit of the central meridian, i.e., zero velocity crossing, as the definition of zero for the new relative phase. The first eight measured values of differential radial velocity have been replotted on Figure 7, shifted to the new relative phase scale.

It is apparent that a point source is a totally inappropriate representation for the purported plage region, but if our assertion is correct that the eighth observation (absolute phase 0.634) represents the setting of the trailing edge of the plage over the receding limb, then any reasonable axial inclination will require a high latitude for that event. This is a stronger argument than any given previously for the active region to be at a high latitude on GL 890.

Returning to Figure 6, we note that the first three or four observations are consistent with a constant value for the peak intensity of Hα, regardless of any interpretation which might be assigned to that behavior. The onset of a steep negative gradient of Hα peak intensities which terminates abruptly with the ninth observation (absolute phase 0.669), and which reduces the peak intensity by 50%, suggests that the observed profile between absolute phases 0.390 and 0.669 is *dominated* by one bright emissive region which is transiting the receding (setting) limb of the star during the time when the intensity of Hα is undergoing its rapid reduction. This interpretation is not unique, and the actual situation may be much more complex in detail, with chromospheric inhomogeneities of surface brightness and fill factors. In the absence of any other evidence, however, we are entreated to follow Ockham's Razor and to

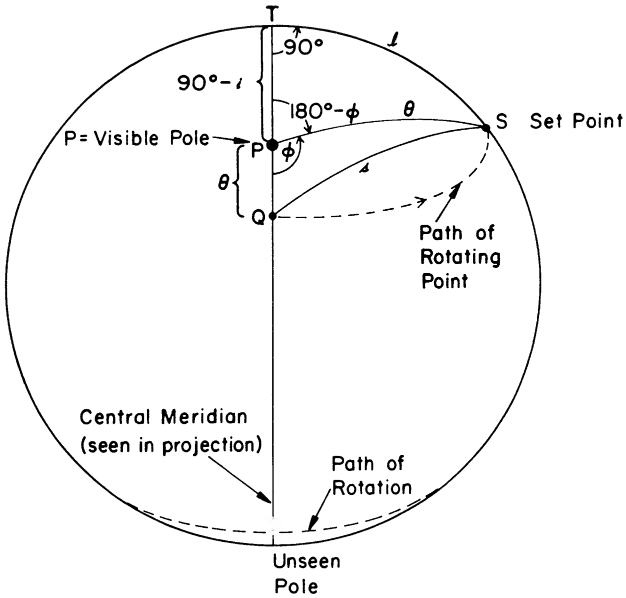

FIG. 8.—Schematic diagram of the spherical geometry of a point source traversing the visible disk of a rotating star.

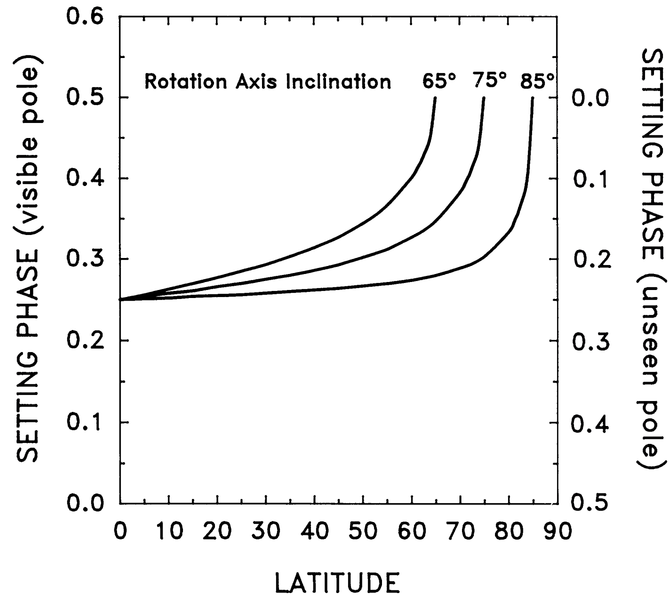

FIG. 9.—Plot of the setting phases for points on a rotating star with various inclinations, as a function of latitude, for both polar zones.

adopt the simplest and least complicated model which is required to account for what is actually observed.

Further discussion of the significance of these phenomena requires a careful examination of the spherical geometry involved with the rising and setting of points on the projected disk of a rotating star.

Figure 8 is a schematic diagram of the projected disk of a rotating sphere with an arbitrary axial inclination (i). A point (Q) is shown transiting the central meridian, and then setting (S) at a phase angle ϕ. The co-latitude (θ) of points Q, S is shown on the diagram for simplicity of illustration, but we shall express all results in terms of the latitude of the points, $\beta(90° - \theta)$. For the special case in which the axis of rotation is in the plane of the sky ($i = 90°$), points at every latitude set at the same relative phase (0.25). However, for all other inclinations, other than zero, that degeneracy is removed, and the limbs can act as scanning boundaries to specify the latitude of a point if the phase angle of its rising or setting can be ascertained. Application of the law of sines and the law of cosines in spherical triangles leads to the relationship

$$\cos(\phi) = -\tan(\beta)\cot(i) . \quad (4)$$

Figure 9 displays this result in graphic form for a few selected axial inclinations which are of particular interest for the study of GL 890. High latitudes near the visible pole extend the setting phase beyond 0.25, whereas those same latitudes (if visible) near the unseen pole retard the setting phase by equal amounts below 0.25. The radial velocity for any point on the disk can now be written as

$$V_r = V_{eq} \sin(i) \cos(\beta) \sin(\phi) . \quad (5)$$

It is now readily seen that, for a small emissive region near the unseen pole, the faster material at the lower latitude edge would be the last to set, whereas at the visible pole the converse effect would occur. The phase dependence of the measured velocities for the first eight observations depicted in Figure 6 is more *simply* explained as a high-latitude plage near the unseen pole. However, that is not required by the observations, because an appropriate adjustment in the distribution of longitudes for such a region can compensate the phase dependence induced by the distribution of latitudes. We have elected to treat the plage as if it were near the unseen pole partly because fewer arbitrary assumptions are required, and because it appears that many events occur in intervals of phase which are short compared to half of the rotation period and which would obtain naturally for regions near the unseen pole. The asymmetry of the points in Figure 7 with respect to the zero crossing of radial velocity requires that the region cannot be symmetrical about a meridian on the star. The zero in differential radial velocity, occurring approximately 0.06 in phase after the onset of setting of the leading edge, implies that it results from an averaging over emissive material which is on both sides of the central meridian. Setting of the leading edge requires a loss of material which contributes positively to the net velocity, yet the velocities continue to become more positive with advancing phase. This circumstance suggests (at the unseen pole) that the faster material at lower latitudes lags behind the higher latitude material in longitude. Ideally, one would like to solve uniquely for at least the latitude of the trailing edge which is the last to set. Unfortunately, there are too many free parameters (e.g., V_{eq}, i, β, and time of transit of central meridian) with too few observational constraints to permit such a solution, even if the simplified model were reasonably correct. The actual (irregular) shape of such a region, its boundaries in latitude and longitude, the complexity of its nonuniform surface brightness, and contamination from other regions, as well as a possible global contribution, render any realistic solution of the complete problem hopeless without the kind of spatial resolution afforded by the disk of the Sun. However, within the confines of the simplified model, equations (4) and (5) permit an iterative scheme which generates a set of possible solutions that can be confined within limits by means of reasonableness arguments. The problem is first parameterized by the selection of a value for V_{eq} and initialized by setting the axial inclination (i) to 90°. Equation (5) can then be used to obtain a starting value for the latitude of the setting point by assuming that the

TABLE 3

SOLUTIONS FOR THE UNSEEN POLE

	$V_{eq} = 75$ km s^{-1}		$V_{eq} = 70$ km s^{-1}		$V_{eq} = 65$ km s^{-1}	
i	β	ϕ	β	ϕ	β	ϕ
90°...	80°29′	0.250	79°47′	0.250	79°00′	0.250
88....	80 18	0.217	79 38	0.219	78 53	0.222
84....	78 44	0.161	78 10	0.166	77 29	0.171
80....	76 08	0.123	75 41	0.129	75 05	0.135
76....	72 58	0.099	72 33	0.104	72 06	0.110
72....	69 30	0.082	69 10	0.087	68 44	0.093
68....	65 48	0.072	65 32	0.076	65 08	0.081
64....	62 05	0.064	61 46	0.068	61 28	0.073
60....	58 12	0.059	57 59	0.063	57 39	0.067

differential radial velocity of the eighth observation defines that event. The inclination is then incremented downward, and the original value for the latitude (β) is used in equation (4) to estimate the new phase angle (ϕ) for setting. That new phase angle, inserted into equation (5), generates a revised estimate of the latitude for the new inclination, which is then returned to equation (4). Convergence is taken to be the set of values of i, β, and ϕ which generates a radial velocity in equation (5) that differs from the observed value by less than the presumed measurement error (taken to be 0.1 km s^{-1}). Table 3 gives the set of solutions obtained in the manner described for three specified values for V_{eq}, and Figure 10 is a schematic depiction of a region having the proper basic structure as it progresses from first to last contact with the receding limb.

Given the known rotation period for GL 890, Table 4 specifies the equatorial velocities which would result for various values of the radius of the star in units of the solar radius. The low-resolution spectra and the photometry of GL 890 given by Pettersen *et al.* (1987) leaves no doubt that the star is an early-type M dwarf. Those authors show that the appropriate radius is between 0.5 and 0.6 solar radii, and they derive a value of 0.58 ± 0.07 $R_{\odot}$. Our selection of equatorial velocities was based upon this information. Furthermore, Young, Skumanich, and Harlan (1984) derive a value of 70 km s^{-1} for V (sin i) directly from the breadth of the photospheric lines; Pettersen *et al.* (1987) confirm that value and put a lower limit of 64 km s^{-1} on the projected equatorial velocity. At an axial inclination of 60°, our highest selected equatorial velocity projects into their lower limit, and they, too, concur that the axial inclination lies between 60° and 90°. We suggest, therefore, that the correct solution for the latitude of the setting portion of the observed plage is within the confines of Table 3. That table admits no latitude below 57°, and the most probable values for all of the other relevant parameters imply that the actual latitude of the point in question is between 65° and 75°. One further (model-dependent) argument can also be put forth in support of that contention. While we have no direct way to infer the time of central meridian transit of the trailing point of the plage region, our model requires that from that time until the time of setting the observed differential radial velocities must all be positive. The interpolated phase for the null of differential radial velocity is 0.18, and the setting phase is between that of the eighth observation (0.24) and the ninth observation (0.28). Therefore, the setting phase of the region at the *lowest* latitude can be no less than the smallest difference between these phases (0.06) and is probably closer to 0.10. Once again, Table 3 requires that such a region be at a latitude of no less than 65° for any reasonable configuration of stellar parameters.

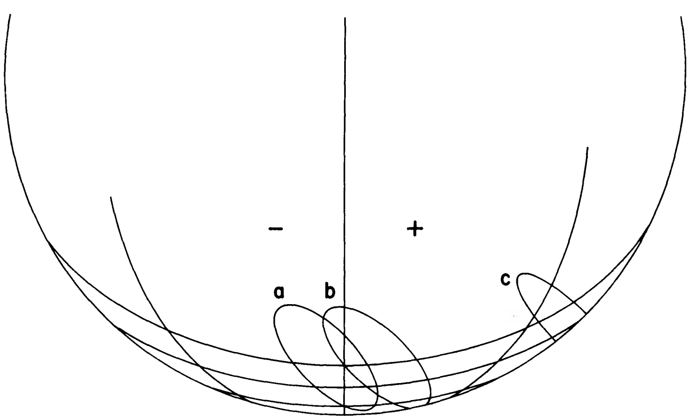

FIG. 10.—Hypothetical schematic of a pseudoplage traversing the visible disk of a rotating star from left to right. Signs indicate the sense of the radial velocity of those regions.

IV. DISCUSSION

While GL 890 is unique among the field dMe stars for its exceptionally rapid rotation, it shares many properties in common with other active (both single and binary) stars, as well as with main-sequence and evolved stars. For example, our premise that most of the excess radiation in Hα arises from a few localized region(s) was also asserted for the RS CVn binary II Peg by Bopp and Noah (1980, and references therein); Bopp and Talcott (1978) suggested that 75% of the Hα flux observed from the RS CVn star UX Ari came from active regions. The reasoning for all of these cases, as well as our own for GL 890, depends heavily on the magnitude of the modulation of Hα and on the presumption that it is caused by the appearance and disappearance of active regions over the approaching and receding limbs. The important point is that our analysis for the latitude of the active region did not require a special assumption which has no precedence among other active stars. Even the high latitude itself, while very much unlike anything observed on the Sun, is not unprecedented in the literature about active stars. Oskanyan *et al.* (1977) suggested spots at very high latitude on BY Dra, with the (appropriate) caveat that such a conclusion is model dependent. Bopp and Evans (1973) made similar statements about both BY Dra and CC Eri, and Vogt and Penrod (1983) suggested that spots on HR 1099 (V711 Tau) migrate from equatorial to polar latitudes. Of perhaps more interest to the case of GL 890 is the analysis of the extremely rapid (K dwarf) rotator in the Pleiades (H II 1883; $P = 0.235$ d) given by Stauffer, Dorren, and Africano (1986), wherein a latitude of 50° is derived for the major spot, with a fill factor of 7.5%. Vilhu, Gustafsson, and Edvardsson (1987) also found that the active region on the rapidly rotating K star HD 36705 is at a "high latitude" (unspecified value). Stauffer, Dorren, and Africano (1987) have reported light curves for seven rapidly rotating K

TABLE 4

RANGE OF POSSIBLE EQUATORIAL VELOCITIES

VELOCITY (km s^{-1})	RADIUS ($R_{\odot}$) 0.7	0.6	0.5	0.4
V_{eq}..............	82	71	59	47

dwarfs in the Pleiades and α Persei clusters, having periods ranging from about 5 hr to 16 hr. Most of their light curves are simple sinusoids with no intervals of constant light, and they state, categorically, that the cause of that behavior is high latitude for the spot regions. Some of their light curves (particularly AP 86; $P = 5.06$ h) exhibit the same morphology shown by the discovery light curve of GL 890; namely, a slow decay to minimum light followed by a more rapid recovery back to maximum. The two most rapid rotators (H II 1883 and AP 86) are reported by those authors to show the same kind of extreme secular alterations of morphology of their light curves as we have found for GL 890. The phenomena which are observed on rapidly rotating, single, cool, main-sequence stars are substantially of the same character, and there is only some apprehension that we may not be interpreting those observations correctly, or entirely without ambiguity.

The weight of evidence favors the existence of spot and plage activity at quite high latitudes on GL 890 and on those stars which are similar to it in both their structure and their rotation. Two different interpretations for such behavior can be suggested at once. Using the solar activity cycle as an exemplar, magnetic activity cycles on other stars may also be characterized by initiation at high latitude, followed by migration to lower latitudes (or perhaps vice versa in some unusual cases which differ appreciably from solar conditions). From that perspective, the extremely rapid rotators may, for reasons not yet clear, have higher starting (or ending) latitudes for their cycles. Conversely, it can be argued that the data currently available are consistent with the notion that, for extremely rapid rotation ($P \lesssim 1$ d), stellar magnetic activity is *confined* to very high latitudes on the surfaces of such stars. In the absence of a thorough theoretical understanding of the mechanism of stellar magnetic activity, a decisive argument for or against either of those interpretations is not forthcoming. The frequency with which high-latitude activity is found on such stars, with a random sampling schedule, provides a tentative empirical argument which favors confinement of the active regions to high latitudes rather than cycling. Clearly, if that could be demonstrated in a compelling fashion, it would have considerable importance for the theory of dynamo-generated magnetic activity. This is one of the ways in which the study of magnetically induced activity on other stars can contribute to the progress of solar physics, and vice versa. Since the discussion of the observations of the Hα profile of GL 890 provided the most convincing argument for the high latitude of the active region, we propose that a suitable test to discriminate between confinement versus cycling would be to make time-resolved spectroscopic observations of the rapidly rotating dMe stars in the Pleiades. Finding active regions at various latitudes on those stars would eliminate the confinement argument definitively, whereas the converse result would make a strong case for confinement. Few, if any, existing telescopes could perform such observations owing to the faint apparent magnitudes of the dMe stars in the Pleiades, but the next generation of proposed large telescopes will be capable of making this critical test.

In a recently published study of the star Xi Boo A, Toner and Gray (1988) demonstrate that a rather large dark spot (which they call a "starpatch") has persisted on this star at a latitude of about 55°. They focus attention on the considerable differences between the properties of the spot on Xi Boo A and those of spots on the Sun. Many of the properties we find in GL 890 are more similar to those reported by Toner and Gray (1988) than to the Sun, even though we have used solar properties as a guide to interpreting some of the properties of GL 890. It is apparent that caution must be exercised in any such attempt at making analogies, and that rotation rates which are significantly faster than that of the Sun may lead to considerably different dynamo-generated properties on the surface of a star.

Additionally, we note that based upon its extremely rapid rotation, one might expect the chromospheric luminosity of GL 890 to be significantly greater than that of other active main-sequence stars of similar spectral type which rotate less rapidly. However, the results presented in preceding sections show that the overall activity of GL 890 (inferred from Hα and Mg II *hk* fluxes and the absence of detectable C IV emission) is similar to that of more slowly rotating dMe stars. This appears to be a confirmation of the saturation of magnetic activity and chromospheric cooling proposed and discussed by Skumanich and MacGregor (1986).

Finally, we address the issue of why such a rapidly rotating star as GL 890 exists among the population of field dMe stars. Pettersen *et al.* (1987) discuss this issue at length, citing numerous speculative scenarios to which we can add no more. We doubt that the explanation will be found in exotic, improbable scenarios. We propose instead that GL 890 is, like all other dMe field stars, much younger than the Sun. The question of why such young stars should coexist in the immediate neighborhood of the Sun, apart from any nearby region of active star formation, is an issue to be addressed in the broader context of stellar evolution, and not in this study of a single star with unusual properties.

We are grateful to the director of the Kitt Peak National Observatory for providing the telescope time necessary to conduct this study and to the technical staff for expert assistance with the CCD system. One of us (A. Y.) wishes to express gratitude to the High Altitude Observatory for providing support during a sabbatical leave and considerable hospitality during an extended visit. Some of the analysis was completed with the computing facilities of the Center for Astrophysics and Space Sciences (CASS), University of California at San Diego, and we are grateful to the director, E. Margaret Burbidge, for making those facilities available to us. Expert assistance with computational codes was provided by Greg Woods (HAO), and by Rich Bentley (CASS), to whom we are grateful.

We appreciate a helpful critical review of the manuscript by D. L. Lambert.

APPENDIX

THE JOURNAL OF PHOTOMETRIC OBSERVATIONS

TABLE 5

Photometry of GL 890

Julian Date[a]	Delta Mag	Julian Date[a]	Delta Mag	Julian Date[a]	Delta Mag	Julian Date[a]	Delta Mag	Julian Date[a]	Delta Mag
3 Sept. 1983	V Filter	4 Sept. 1983	V Filter	3 Aug. 1984	y Filter	1 Sept. 1984	y Filter	13 Oct. 1984	V Filter
580.8343	1.501	581.8959	1.514	915.8480	1.504	944.8008	1.467	986.6951	1.563
580.8382	1.502	581.8988	1.509	915.8562	1.502	844.8060	1.470	986.6991	1.565
580.8414	1.508	581.9017	1.508	915.8638	1.499	944.8115	1.474	986.7055	1.567
580.8450	1.518	581.9059	1.506	915.8757	1.488	944.8165	1.463	986.7096	1.559
580.8507	1.512	581.9087	1.500	915.8840	1.484	944.8202	1.473	986.7134	1.566
580.8545	1.514	581.9118	1.498	915.8916	1.489	944.8234	1.473	986.7299	1.566
580.8582	1.524	581.9159	1.500	915.9141	1.470	944.8317	1.483	986.7334	1.562
580.8775	1.516	581.9218	1.488	915.9259	1.476	944.8354	1.479	986.7392	1.569
580.8813	1.521	581.9259	1.483	915.9342	1.479	944.8446	1.489	986.7569	1.566
580.8843	1.527	581.9286	1.484	4 Aug. 1984	y Filter	944.8496	1.486	986.7613	1.565
580.8872	1.530	581.9314	1.476	916.8438	1.497	944.8533	1.490	986.7721	1.577
580.8913	1.528	581.9357	1.476	916.8516	1.496	944.8575	1.493	986.7755	1.567
580.8954	1.529	581.9390	1.472	916.8599	1.494	944.8646	1.485	986.7792	1.567
580.9015	1.534	581.9417	1.469	916.8702	1.503	944.8695	1.486	986.7834	1.574
580.9054	1.531	581.9480	1.471	916.8779	1.503	944.8731	1.485	986.7872	1.571
580.9117	1.531	581.9512	1.461	916.8863	1.506	944.8769	1.506	986.7969	1.563
580.9151	1.530	5 Sept. 1983	V Filter	916.9020	1.508	944.8822	1.492	986.8027	1.567
580.9185	1.534	582.7646	1.514	916.9139	1.506	944.8858	1.501	986.8075	1.565
580.9249	1.538	582.7738	1.502	916.9216	1.498	944.8920	1.503	986.8122	1.559
580.9280	1.536	582.7830	1.490	916.9293	1.505	944.8959	1.504	986.8182	1.559
580.9334	1.536	582.7875	1.484	916.9368	1.500	944.9052	1.507	986.8230	1.554
580.9378	1.526	582.7945	1.481	916.9452	1.491	944.9102	1.494	986.8292	1.547
580.9446	1.545	582.8025	1.468	916.9560	1.483	944.9138	1.488	986.8338	1.561
4 Sept. 1983	V Filter	582.8071	1.462	916.9641	1.479	944.9187	1.501	986.8376	1.543
581.7637	1.533	582.8137	1.451	916.9741	1.505	944.9229	1.503	986.8421	1.543
581.7699	1.531	582.8183	1.457	31 Aug. 1984	y Filter	944.9286	1.508	12 Nov. 1984	V Filter
581.7728	1.532	582.8259	1.449	943.8381	1.508	944.9325	1.514	1016.5990	1.547
581.7757	1.532	582.8306	1.451	943.8444	1.497	944.9374	1.496	1016.6034	1.547
581.7795	1.538	582.8364	1.450	943.8491	1.502	944.9439	1.488	1016.6085	1.550
581.7820	1.522	582.8452	1.444	943.8548	1.494	11 Oct. 1984	V Filter	1016.6132	1.555
581.7847	1.538	582.8497	1.441	943.8580	1.489	984.7220	1.540	1016.6165	1.550
581.7889	1.537	582.8554	1.449	943.8614	1.490	984.7268	1.542	1016.6367	1.556
581.7916	1.537	582.8599	1.446	943.8695	1.487	984.7329	1.544	1016.6409	1.557
581.7943	1.535	582.8677	1.448	943.8728	1.480	984.7376	1.552	1016.6460	1.564
581.7970	1.540	582.8738	1.447	943.8788	1.472	984.7475	1.555	1016.6509	1.561
581.8029	1.536	582.8793	1.451	943.8823	1.479	984.7554	1.540	1016.6549	1.565
581.8055	1.535	582.8897	1.455	943.8876	1.481	984.7600	1.557	1016.6667	1.571
581.8092	1.543	582.8953	1.454	943.8908	1.476	984.7659	1.567	1016.6717	1.569
581.8130	1.542	582.9008	1.463	943.8942	1.476	984.7723	1.558	1016.6773	1.570
581.8161	1.541	582.9087	1.465	943.9010	1.478	984.7804	1.558	1016.6825	1.572
581.8216	1.543	582.9188	1.476	943.9044	1.476	984.7904	1.570	1016.6867	1.572
581.8245	1.537	582.9243	1.472	943.9078	1.484	984.7952	1.557	1016.7031	1.581
581.8272	1.539	582.9289	1.477	943.9126	1.477	984.8008	1.558	1016.7074	1.579
581.8310	1.548	582.9367	1.481	943.9164	1.480	984.8810	1.554	1016.7115	1.569
581.8337	1.545	582.9424	1.482	943.9217	1.461	984.8815	1.560	1016.7174	1.570
581.8370	1.542	582.9498	1.485	943.9250	1.459	13 Oct. 1984	V Filter	1016.7217	1.576
581.8442	1.545	2 Aug. 1984	y Filter	943.9316	1.467	986.6491	1.543	1016.7261	1.559
581.8475	1.544	914.8960	1.491	943.9429	1.473	986.6551	1.551	1016.7520	1.545
581.8674	1.537	914.9101	1.483	1 Sept. 1984	y Filter	986.6602	1.553	1016.7591	1.547
581.8711	1.534	914.9212	1.493	944.7679	1.480	986.6688	1.559	1016.7636	1.551
581.8756	1.530	914.9442	1.496	944.7733	1.485	986.6747	1.556	1016.7683	1.544
581.8788	1.531	914.9593	1.508	944.7816	1.470	986.6785	1.558		
581.8840	1.519	3 Aug. 1984	y Filter	944.7877	1.471	986.6828	1.559		
581.8916	1.496	915.8378	1.499	944.7934	1.471	986.6867	1.569		

[a] Heliocentric epoch 2,445,000.

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