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COORDINATED OPTICAL AND ULTRAVIOLET OBSERVATIONS OF IM PEGASI

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ABSTRACT

IM Peg (HR 8703, HD 216489) is a moderately active, single-lined RS CVn binary for which we have obtained contemporaneous *IUE* and optical observations over two seasons. The UV lines are modulated with phase such that the UV emission maxima occur simultaneously with the visible light curve minimum. The UV emission-line modulation increases as a function of height, suggesting that the emission originates in loop-like structures associated with starspot regions. Optical lines such as Hα, Hβ, and the Ca II infrared triplet show some degree of modulation as well. Hα variability is dominated by stochastic events, while Hβ shows excess absorption relative to a standard star. Thus, the hydrogen line emission may not be correlated with the starspots responsible for the photometric and UV variability, but rather may arise from an extensive chromospheric network. The Ca II IRT shows a clear modulation with phase; the degree of the modulation suggests that it arises in the chromosphere.

IM Peg appears to fit the solar paradigm generally used to explain RS CVn activity much better than more active systems, for which simple extrapolations of the Sun should be viewed with caution. For less active systems such as IM Peg, however, the visible lines alone appear to provide an excellent chromospheric diagnostic.

Subject headings: stars: binaries — stars: emission-line — stars: individual (IM Peg) — ultraviolet: spectra

I. INTRODUCTION

IM Pegasi (HR 8703, HD 216489) is a long-period RS CVn binary of the single-lined noneclipsing type. The spectral type of the visible star is K1 III–IV (Strassmeier *et al.* 1989). The spectroscopic period of the system is 24.649 days and the photometric period is 24.40 days (Strassmeier *et al.* 1989); IM Peg is thus nearly a synchronous system. The distance of the star has been variously derived in the range of 50 pc. (Majer *et al.* 1986) to 200 pc. Eker (1984) quoted values for the radius of the primary center around 12–15 $R_{\odot}$. Poe and Eaton (1983) derived a value for the system inclination of 60°.

Photometry has been obtained by many investigators over the years. Eaton *et al.* (1983) recorded $\Delta V = 0.16$ mag, but noted that the range in brightness was itself variable. Hall (1981) found that ΔV ranged from 0.16 to 0.23 mag. More recently, Strassmeier *et al.* (1989) indicated that the range in magnitudes over the past four seasons has been roughly constant at ∼0.20 mag. Eaton *et al.* (1983) found that IM Peg displayed a migration of the position of the photometric minimum with a 6.5 yr period which may be caused by spot evolution and differential rotation. The same effect is visible in the data of Strassmeier *et al.* (1989). However, this effect may be due to nonsynchronicity of the periods of rotation and revolution; the observed differences in the periods would generate an apparent migration with a 6.6 yr period.

Excess emission in the Ca II H and K lines was first noted by Herbst (1973), and later by Hall (1976) and Cowley and Bidelman (1979), who described the emission as strong. Bopp and Talcott (1978), in their survey of Hα emission in RS CVns, found that Hα in IM Peg was filled in, although not completely in emission. Walter and Bowyer (1981) report a soft X-ray luminosity for IM Peg of 4×10^{31} ergs s^{-1}, based on a distance of 60 pc.

II. OBSERVATIONS AND DATA REDUCTION

We obtained a total of 10 *IUE* spectra of IM Peg during the summers of 1985 and 1986. Spectra were all low-dispersion SWP, with exposure times ranging from 20 to 120 minutes (see Table 1). Image SWP 26349, from 1985 July 5, was a flare episode and is analyzed elsewhere (Buzasi, Huenemoerder, and Ramsey 1987). *IUE* data were reduced at the Pennsylvania State University using the Black Moshannon Observatory (BMO) FORTH software package. A typical reduced spectrum is shown in Figure 1. It displays emission lines similar to those seen in other long-period RS CVn stars (see, e.g., Baliunas, Guinan, and Dupree 1984); these include N V, O I, C II, Si IV, C IV, He II, C I, Si II, and Si III and represent a wide range of excitation and ionization conditions. The prominent Lyα feature is contaminated by geocoronal emission and was not analyzed. Continuum emission is quite flat over the entire *IUE* spectral range and the level of emission is low.

Seventeen optical observations of IM Peg were also obtained during the summer of 1985 (see Table 2), using the 1.6 meter telescope at the Black Moshannon Observatory. The spectrograph used was a fiber-coupled echelle, which gave resolution $\lambda/\Delta\lambda = 12{,}000$ and nearly complete wavelength coverage from 3900 to 8500 Å (Ramsey and Huenemoerder 1986), when used with an RCA CCD. The typical exposure had $S/N \geq 100$. Analysis of the optical spectra focused on the Hα, Hβ, and Ca II IRT lines, as these are known to be good indicators of activity on the Sun (Zirin 1988, Labonte 1986*a*, *b*) and on other active stars (Huenemoerder and Ramsey 1987). The optical observations were contemporaneous with those in the UV and were frequently taken within hours of the *IUE* spectra.

Optical spectra were reduced using the BMO Frame Processing System (BFPS) echelle reduction package developed at Penn State (Rosenthal 1986). The extracted, flat-fielded, and

[1] Guest observer with the *IUE* satellite, which is sponsored and operated by the National Aeronautics and Space Administration, the Science Research Council of the United Kingdom, and the European Space Agency.

TABLE 1

IUE OBSERVATION LOG

Date	Image Number	Resolution	Exposure Time
1985 Jul 2	SWP 26334	Low	50
1985 Jul 5	SWP 26349	Low	65
1985 Jul 12	SWP 26403	Low	25
1985 Jul 16	SWP 26423	Low	50
1985 Jul 20	SWP 26449	Low	20
1985 Jul 31	SWP 26507	Low	50
1985 Aug 6	SWP 26562	Low	30
1985 Aug 11	SWP 26589	Low	60
1986 May 29	SWP 28400	Low	120
1986 May 29	SWP 28403	Low	65

TABLE 2

OPTICAL OBSERVATION LOG

UT Date	Phase
1985 Jul 4	0.475
1985 Jul 4	0.475
1985 Jul 5	0.515
1985 Jul 8	0.634
1985 Jul 11	0.756
1985 Jul 14	0.879
1985 Jul 17	1.001
1985 Jul 17	1.001
1985 Jul 22	1.200
1985 Jul 23	1.250
1985 Jul 24	1.300
1985 Jul 27	1.400
1985 Aug 2	1.646
1985 Aug 2	1.652
1985 Sep 29	3.997

continuum-normalized spectra were then examined for stellar activity features by the spectral subtraction technique. A standard star of similar spectral type to IM Peg was artificially Doppler broadened and velocity shifted to match the parameters observed in IM Peg, and then subtracted from the IM Peg spectrum. The result is a spectrum which is generally zero except in regions where chromospheric and transition region activity gives rise to excess emission. A sample indicating the procedure is illustrated by Figure 2. Note that the subtracted optical spectrum resembles the *IUE* spectrum in that there is essentially no continuum. Line fluxes were then measured from the subtracted spectra. Discussions of the merits and difficulties of the subtractin process are given in Buzasi (1989) and Huenemoerder, Buzasi, and Ramsey (1989).

III. ANALYSIS

a) Ultraviolet Lines

Based on a solar paradigm, we can divide the UV lines into three groups. First, we consider those emanating from the chromospheric region. These lines are O I and Si II and represent the low-temperature parts of the extended stellar atmosphere (see, e.g., Buzasi, Huenemoerder, and Ramsey 1987; Brown and Jordan 1981). Lines derived from regions of higher excitation temperature represent the stellar transition region and include C IV, N V, Si IV, and C II. Finally, He II represents the high chromosphere and low corona, as it is formed only at very high temperatures.

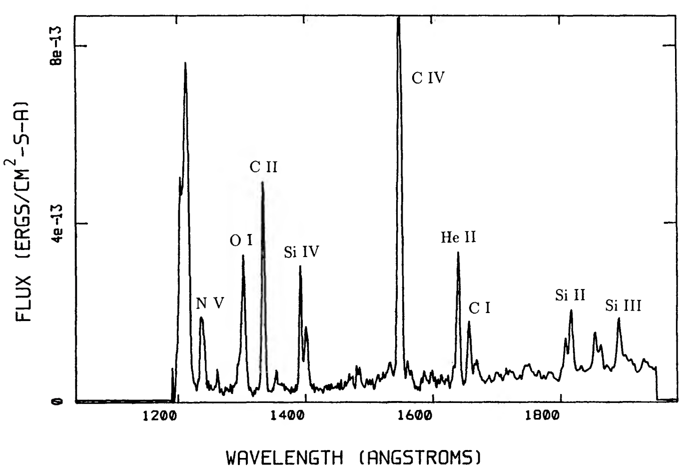

FIG. 1.—A typical reduced *IUE* spectrum of IM Peg (SWP 28400). Lyα is saturated.

In Figure 3, we plot the indicators described above a function of phase, using the ephemeris 2422243.316 + 24.649 E (Strassmeier *et al.* 1988). Clearly variations in all three regions are well correlated. Further, the observed modulation is a function of temperature and thus height. If we define modulation as

$$M = \frac{\max - \min}{\max + \min},$$

then the modulation of the chromospheric lines is 0.25, while that of the transition region lines is 0.53 and of He II is 0.67. Strassmeier *et al.* (1989) show that IM Peg's phase of minimum light in 1985–86 is ≈0.87 (converting to our ephemeris). The correspondence between the photometric minimum and the UV line emission maximum from all heights is obvious, leading to the conclusion that the UV emission regions are correlated with starspots.

b) Optical Lines

For application of the subtraction procedure we chose as a standard star ψ UMa (HR 4335), which has spectral type

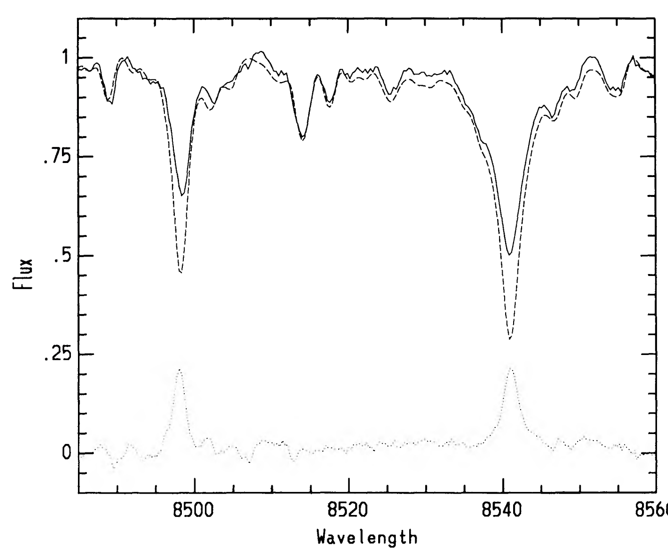

FIG. 2.—An example of the subtraction process discussed in the text, in the region of the Ca II IRT. The solid line is the observed spectrum, while the dashed line represents the synthetic spectrum, and the dotted line the result of the subtraction process.

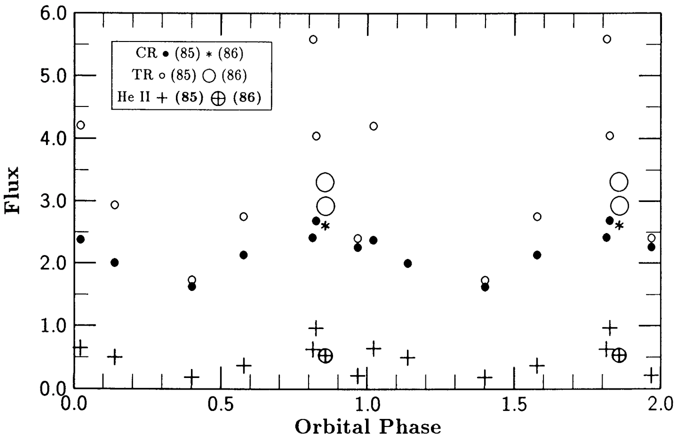

FIG. 3.—The ultraviolet activity indices defined in the text are shown as a function of phase. Small open circles represent the TR flux in 1985, large open circles the TR flux in 1986, closed circles the CR flux in 1985, asterisks the CR flux in 1986, plus signs the He II flux in 1985, and crossed circles the He II flux in 1986. The indicators are quite consistent from season to season. Note the increased modulation with height. Data have been plotted twice to show continuity at $\phi = 1$.

K1 III. The standard star fits to inactive regions of the IM Peg spectrum yield a value for $v \sin i$ of 32.4 ± 5.0 km s^{-1}. This corresponds to a stellar radius of $15.5 \pm 2.4\ R_{\odot}$, in general agreement with values obtained by other authors, and with that predicted by the Barnes-Evans relation (Barnes and Evans 1976; Barnes, Evans, and Parson 1976; Barnes, Evans, and Moffett 1978). Applying the relations given in Allen (1974, p. 197), we also obtain a distance to the star of 69 ± 11 pc, if the effective temperature is taken as 4300 K. Below we consider the subtracted line fluxes in Hα, Hβ, and the Ca II infrared triplet (IRT). Measurements are of the subtracted line areas, which are equivalent to an excess equivalent width.

i) *Hydrogen Lines*

The Hα excess emission as a function of phase is shown in Figure 4. Although a weak modulation is seen, in general the activity level is nearly constant, with a mean excess emission level of 0.99 ± 0.20 Å EW. The Hβ line (Fig. 5) displays a somewhat more peculiar feature; the subtracted line has negative flux, indicating that the Hβ absorption feature in IM Peg is deeper than that in the standard star. The Hβ excess absorption has a mean of 0.54 ± 0.21 Å EW. This excess absorption may be caused by the fact that Hα goes into emission at smaller column densities than does Hβ (see Cram and Mullan 1985), or may be due simply to a mismatch of the standard star and IM Peg. Further, the Hβ feature does not appear to vary with phase. This would appear to indicate that the hydrogen emission is not correlated with the starspots responsible for the photometric variability. Hydrogen emission may arise from globally distributed structures, perhaps similar to the chromospheric network on the Sun, or from circumpolar regions.

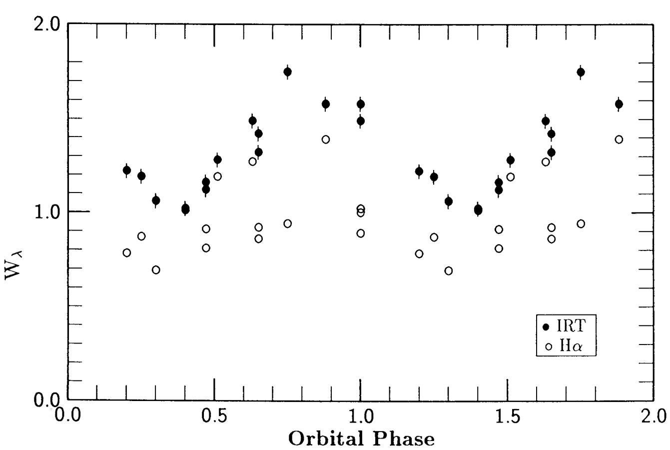

FIG. 4.—Hα and the Ca II IRT excess line fluxes as a function of phase. Both are modulated, and they track one another well. The phase of maximum excess flux corresponds with the photometric minimum. Uncertainties ($\pm\sigma$) for Hα are equal to the symbol size, and are shown for the IRT. Data have been plotted twice to show continuity at $\phi = 1$.

ii) *Calcium IRT*

The sum of $\lambda\lambda$8498 and 8542 Ca II IRT excess emission is also plotted in Figure 4. This emission is clearly correlated with phase and the IRT light curve is quite similar to those seen in the UV lines discussed above. The level of modulation in the IRT is 0.26 and thus it appears to emanate from the same regions as the O I and Si II lines, namely, the chromosphere. The mean excess emission in the two IRT lines available, $\lambda\lambda$8498 and 8542, is 0.57 ± 0.09 and 0.71 ± 0.10 Å EW, respectively.

IV. DISCUSSION

Several points can be made on the basis of the data presented above. The UV line emission arises in regions which appear to be concentrated around the starspots believed responsible for the observed photometric light curve. A substantial fraction of the Ca II IRT emission probably also arises from an area associated with starspot activity. In addition, the IRT emission is formed relatively low down in the atmosphere, in the chromosphere. We know this because the IRT variations are well correlated in both phase and magnitude with those of UV lines known to arise from this area. Finally, the hydrogen line emission clearly does not arise predominantly from regions associated with starspots. It shows little or no variability as a function of phase and thus must either have a large polar component or be more evenly distributed across the stellar surface. If the latter is the case, we can theorize that the Hα emission on IM Peg arises primarily from the network and is strengthened only slightly, if at all, in the plage or active regions presumably associated with starspots.

One interesting facet of the observed UV line variations in the increase in flux modulation as a function of height. If the magnetic fields which constrain the active structures dilate higher in the atmosphere, we would expect the reverse to be the case, as energy input is spread out over a larger volume, as they do in the quiescent Sun (Athay 1976, p. 173). This implies that the observed modulated emission is produced by structures in which the magnetic field lines do not diverge with height, such as loops. In loops, the area decreases as a function of height; the same energy input thus would produce a greater effect at the top of the loop (which is presumably hotter), where the volume available for energy deposition is smaller. A related possibility is that only a fraction of the total number of loops reaches high into the transition region. In this case, since only a fraction of the loops is responsible for high-temperature line radiation, these lines would be expected to display higher sensitivity to energy input than the lines characterized by a lower temperature. While some of the UV and visible emission may be due to enhanced magnetism in network-like structures, the modulated portion of the emission appears to arise from loop-like features similar to those seen on the Sun.

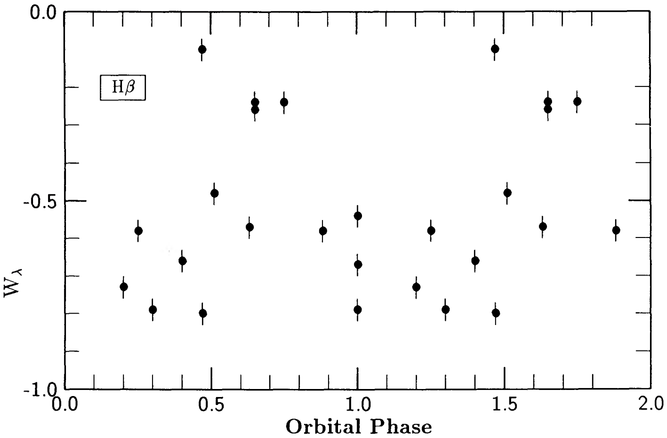

FIG. 5.—Hβ excess flux as a function of phase. The "excess" is negative in this case; Hβ shows excess *absorption*. The minimum absorption corresponds to the phase of greatest Hα and Ca II IRT excess and minimum light. Uncertainties ($\pm\sigma$) are shown by the vertical bars. Data have been plotted twice to show continuity at $\phi = 1$.

Using the distance derived above enables us to calculate the line losses in each region of the atmosphere. Doing so yields a value of 8.0×10^4 ergs cm^{-2} s^{-1} for the CR lines and 2.0×10^5 ergs cm^{-2} s^{-1} for the TR lines. Applying the same procedure to He II gives a loss rate of 2.0×10^4 ergs cm^{-2} s^{-1}. However, the ionization of helium in the chromosphere arises through high-energy photon input from the corona and thus this loss rate, though *related* to the loss rate from the corona, does not well represent it. We will not consider helium further. Examination of archival LWR spectra of IM Peg (images LWR 9680 and 9681) shows that the typical flux in the UV Mg II lines is 3.29×10^{11} ergs cm^{-2} s^{-1} $Å^{-1}$, which corresponds to a radiative loss rate of 1.3×10^6 ergs cm^{-2} s^{-1}. In the Sun, the Mg II lines are formed at heights similar to those of the Ca II lines, in the chromosphere.

If the stellar continuum at the Hα and Ca II IRT lines is considered to be the Planck function, then simple calculations reveal that the loss rate from Hα is 1.5×10^5 ergs cm^{-2} s^{-1} and that from the IRT is 6.8×10^5 ergs cm^{-2} s^{-1}. The assumption of the Planck function means that these values are upper limits; however, in this red part of the spectrum, $I_\nu = B_\nu$ is likely to be a good approximation.

In the Sun, the species discussed above represent the major radiative loss paths (Avrett 1981), and, based on a solar paradigm, we would expect IM Peg to behave similarly. It is apparent that energy loss directly from the chromosphere is very important, and in fact the chromosphere appears to be the dominant loss region in IM Peg. This situation is similar to that seen in the Sun (Avrett 1981; Athay 1976), where energy loss from the chromosphere exceeds that from the upper, more rarefied regions.

A solar paradigm is generally used to explain activity on RS CVn stars. Recently it has been noted (see, e.g., Huenemoerder, Buzasi, and Ramsey 1989) that for extremely active stars such as UX Ari and HR 1099 (V711 Tau) use of such a paradigm must be approached with care. On stars with large regions of extreme activity, even the "quiescent" regions of the atmosphere must be disturbed to some unknown but possibly large degree. This is empirically apparent from the lack of good correlations between such indicators as line flux and phase; correlations that would be expected from a solar paradigm. IM Peg, on the other hand, is a much less active star than the shorter period RS CVns mentioned above, perhaps due to its longer period (see, e.g., Buzasi, Huenemoerder, and Ramsey 1987). This appears to translate into much better adherence to the solar paradigm. Correlations are seen and are generally (with the puzzling exception of Hβ) readily explicable in terms of a solar-like model. For mildly active RS CVn stars, then, the visible lines alone serve well as chromospheric diagnostics.

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