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HYDROMAGNETICS AND PERIOD CHANGES IN RR LYRAE STARS

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Balázs-Detre and Detre have drawn an interesting parallel between the observed time scales of variability in the sun and in RR Lyrae stars. Additional information is presented here to support their conjecture that an analog of the solar magnetic cycle is operating in RR Lyrae stars. Rough considerations of the expected changes of photospheric radius and of magnetic energy content during a magnetic cycle suggest that the pulsation periods of these stars should also change in time. Within the large observational and theoretical uncertainties, the predicted period changes are compatible with those observed.

Key words: magnetic cycles—period changes—RR Lyrae stars

I. Introduction

Many RR Lyrae stars are not precise clocks as far as their pulsation periods are concerned. The periods change in time. Although the normal process of evolution of these stars across the horizontal branch will produce a gradual period change, this is much too slow to account for the most rapid of the changes that are observed (Sandage 1957; Belserene 1964; Stothers 1966; Coutts and Sawyer Hogg 1969; Iben and Rood 1970). On the other hand, the sudden structural reorganization that occurs inside the stars just before they leave the horizontal branch produces a small "kink" in their evolutionary tracks that could conceivably account for both the rapid increases and decreases of period (Stothers 1966; Sweigart and Demarque 1973; Sweigart and Renzini 1979). Although the nature of this "kink" is different in the stellar models used by Stothers and by Sweigart et al., the distinction turns out to be unimportant here, because more detailed work has failed to account for the period changes by this simple approach (Sweigart and Renzini 1979). Thus, for example, observed stars showing rapid period changes are actually fairly common, instead of being fairly rare, among RR Lyrae stars. Furthermore, in contradiction to what is predicted, one finds no obvious luminosity or effective temperature difference between stars with increasing and decreasing periods. And, finally, an unexpected abruptness (or even sign reversal) characterizes some of the observed period changes. This last observation would also rule out a binary-motion interpretation (Coutts 1971) in some cases. Very recently, Sweigart and Renzini (1979) have proposed that random mixing events occurring in the semiconvective zone that surrounds the convective core could produce the observed period changes. We endorse their notion of convective instability somewhere in the star being (at least in part) responsible, but we prefer to look directly to the outer, pulsating layers for a mechanism.

Since the envelope of an RR Lyrae star is convectively unstable in the hydrogen and helium ionization zones, we could reasonably suppose that local turbulent motions might interfere directly with the otherwise periodic pulsational motions of the envelope. Deupree's (1977) two-dimensional calculations of large-cell convection in the envelopes of RR Lyrae stars are too coarse to detect period changes as small as those observed. But, in any case, period changes due to convective motions would be expected to occur on a time scale of hours to days, to be random in sign, and therefore not to accumulate over a time base of years.

Rather, we envisage the kind of slower period changes that might be induced by an analog of the processes responsible for the various solar activity cycles. In section II, we discuss briefly what is most important in the relevant solar processes, and then we turn, in section III, to an application of the solar analogy to RR Lyrae stars.

II. The Sun

In the case of the sun, a still very poorly understood mechanism involving convection, nonuniform rotation, and magnetic fields produces the observed sunspot cycle of about 11 yr, the magnetic cycle of 22 yr, and the even longer, but much less regular, cycles that are represented by the 80-yr variation of sunspot numbers and by the even more extreme prolonged minima in solar activity (Eddy 1976).

If the observed magnetic fields are actually generated within the convection zone and are carried up to the surface by the process of "magnetic buoyancy" (Parker 1955), then it is possible to show that a flux tube of magnetic intensity H will rise from a depth h, where the mass density is ρ, in a time proportional to $h(4\pi\rho)^{1/2}/H$. The constant of proportionality is, unfortunately, difficult to estimate: Parker (1977) gives a simple value ~ 1; Acheson (1979) suggests $\sim 10^3$; but more detailed considerations by Parker (1974) himself have indicated that the true uncertainty in this type of calculation reaches 11 orders of magnitude! Nevertheless, by making judicious choices of h, H, and the proportionality constant, one can of course match the observed time scale of 11 yr and the observed field strengths of 10^2–10^3 gauss. That the magnetic cycle is exactly twice as long as the average sunspot cycle follows in a simple way from the logic of the dynamo model (Parker 1970); but the much longer cycles that are also observed have a completely unknown origin. Recently, Layzer, Rosner, and Doyle (1979) have rejected the dynamo model and have proposed an entirely new theory, which will be discussed below. It is worth mentioning here that the lengths of all these various cycles exceed by many orders of magnitude the fundamental pulsation period of $\sim$ 1 hr (Brown, Stebbins, and Hill 1978), the mean rotation period of 25 days, and the convective overturning time of several weeks.

Possibly associated with one or more of these observed cycles is a quasiperiodic variation of the sun's radius that has been consistently reported by numerous observers since its discovery by Secchi and Rosa (1872). Although the reality of this variation has been sometimes questioned (e.g., Auwers 1886, 1887; Gething 1955), it appears to have an average amplitude of about 0.02% and to follow more or less the 11-yr sunspot cycle (e.g., Meyermann 1951; Giannuzzi 1955, 1957; other references in Gething 1955). Meyermann's work indicates that radius maximum may occur around the time of sunspot maximum rather than around the time of sunspot minimum, as Secchi and Rosa (1872) and Wolf (1884) had earlier found.

There is, however, considerable uncertainty in the true period of variation. Giannuzzi (1955, 1957) actually preferred a basic cycle of 22 to 23 yr, modulated by a shorter cycle of 7 or 8 yr. A resolution of this question could come from long-term studies of the variability of the solar constant (and, possibly, of the photospheric spectrum). At present, only an upper limit of a few tenths of a percent in the possible variation of the solar constant (Fröhlich 1977; Willson and Hickey 1977; Foukal, Mack, and Vernazza 1977) and, worse, of about 2% in the possible variation of the solar effective temperature (Pierce and Allen 1977) can be assigned from the available data. But for our rough purposes, it is sufficient to adopt $P \sim 22$ yr and $\delta R/R \lesssim 10^{-4}$ as the characteristics of the radius variation, with the understanding that $\delta R/R$ could actually be very close to zero. This conclusion is supported by the independent evaluation by Sofia et al. (1979) of the old radius measurements.

III. RR Lyrae Stars

It is now believed that RR Lyrae stars are multiperiodic on a number of differing time scales, just as is the sun. In addition to the basic pulsation period of about half a day, a longer period associated with changes in the light and radial-velocity curves—the Blazhko effect—is known to exist in many RR Lyrae stars (see Szeidl 1976). The observed period of this effect ranges from 12 to 537 days. There are also slow modulations of the Blazhko effect that occur on a time scale of 4 to 10 yr. For two RR Lyrae stars (RR Geminorum and SW Andromedae) the effect has even entirely disappeared for many decades. Other RR Lyrae stars have not been known to show the effect at any time.

Balázs-Detre (1959) has made an interesting suggestion that, if RR Lyrae stars are oblique magnetic rotators, then the period of the Blazhko effect could be intepreted as the surface rotation period of the star (see also Detre 1962; Balázs-Detre and Detre 1962). Some support for this idea was found in Babcock's (1955, 1958) measurement of a slowly varying magnetic field (+1200 to −1600 gauss) in RR Lyrae itself. Although Babcock's data are very few (and include a number of more rapid variations in the magnetic field intensity), Detre and Szeidl (1973) have been able to extend Balázs-Detre's suggestion by noticing that the extreme 4-yr variation in the 41-day Blazhko effect of RR Lyrae could be due to an intrinsic magnetic cycle in the star, resembling the solar cycle (see also Detre 1969). They therefore suggested that Preston's (1967) inability to confirm Babcock's detection of a magnetic field could be due to the star's being in magnetic minimum at the time when Preston made his observations (in 1963–64). We would add here that the apparent absence of the Blazhko effect in many RR Lyrae stars could be simply the analog of the long minimum of the 80-yr cycle (or else of the even more extreme prolonged minima) in the case of the sun. Thus, the sign of an impending cessation of the Blazhko effect could be a slight shortening of the period of the Blazhko effect, in analogy with the shortening of the sun's rotation period just before the long Maunder minimum (Eddy, Gilman, and Trotter 1977; Herr 1978). This shortening of the period would have to be disentangled from the already established irregular variations of the period, which, in the picture presented here, are to be interpreted as due to small, statistical fluctuations of the magnetic field configuration.

A comparison of the observed time scales of variability for RR Lyrae and for the sun is instructive:

Period	RR Lyrae	Sun
Pulsation	14 hr	1 hr
Rotation	41 days	25 days
Magnetic ($P/2$)	4 yr	11 yr .

In addition, the observed magnetic field intensities are comparable in order of magnitude: 10^3 gauss (global) for RR Lyrae and 10^2–10^3 gauss (local active regions) for the sun. But because of the enormous uncertainties in solar hydromagnetic theory, no prediction for the time scale of the magnetic field of either star can be ventured very safely. Nonetheless, both stars do have convective envelopes (which are also in slow rotation), and, if we make the crude assumption that energy is equipartitioned between the magnetic and turbulent fields, we may roughly estimate the maximum magnetic field strength H in the turbulent layers (which extend up to the visible surface) by using simple mixing-length theory and the equation

$$H^2/8\pi \approx 1/2\ \rho v_{\mathrm{turb}}^2 \quad .$$

This yields $H \sim 10^2$ to 10^3 for both stars. We may conclude that RR Lyrae is a fair analog of the sun. This should be true of other RR Lyrae stars as well.

To return to the question of the observed period changes in these stars, we note that the average measured rate of change is $|P^{-1}\ dP/dt| \approx 0.3$ cycle per 10^6 yr; observations also indicate that, between successive period changes, there is probably an interval of about 100 yr (Sweigart and Renzini 1979). Therefore a single period change amounts to $\delta P/P \approx 3 \times 10^{-5}$.

To compute the theoretically expected period change, we adopt Chandrasekhar and Limber's (1954) general variational result for the pulsation period P of a magnetic star (or, here, of the outer mass layers of such a star):

$$P = \left[\frac{4\pi^2 I}{(3\langle\Gamma_1\rangle - 4)(|W| - E_{\mathrm{mag}})} \right]^{1/2} \quad ,$$

where

$$E_{\mathrm{mag}} = \int (H^2/8\pi)\, dV \quad ,$$
$$W = -\int G\mathfrak{M}(r)\, r^{-1}\, d\mathfrak{M}(r) \quad ,$$
$$I = \int r^2\, d\mathfrak{M}(r) \quad ,$$

and the integrals extend over the pulsating layers. The change in period induced by the introduction of the magnetic field is given by

$$\frac{\delta P}{P} = \frac{3}{2}\frac{\delta R}{R} + \frac{1}{2}\frac{E_{\mathrm{mag}}}{|W|} \quad .$$

Evidently the magnetic field affects the period both through the change in radius (as in the case of the ordinary harmonic law $P\langle\rho\rangle^{1/2} = $ constant) and through the change in total energy content.

In a typical RR Lyrae model, $|W| \sim 10^{45}$ erg within the star's outer, pulsating layers, whose effective "base" is chosen so that the variational expression for P gives the observed half-day period. To allow for the magnetic field, let us first suppose that it is produced solely by dynamo action operating in the strongly convective layers. By assuming approximate equipartition of the magnetic and turbulent energies, we find that E_{mag} ranges from 10^{35} to 10^{36} erg across the instability strip. If all this magnetic energy were to be destroyed during the course of a magnetic cycle, the change in pulsation period (other things being equal) would be $\delta P/P \sim 10^{-9}$. Even this extremely small value is probably an exaggeration, because the turbulent layers lie at $r/R > 0.94$ whereas the pulsation period is determined mostly by conditions near $r/R = 0.7$ (Epstein 1950).

In order to achieve a significant change of period ($\delta P/P \sim 10^{-5}$), we could imagine a strong magnetic field *below* the convective layers. If, for example, the magnetic field averaged over a spherical shell is assumed to exert a pressure that is an approximately uniform multiple ν of the thermodynamic pressure (as a function of depth), then we find that the minimum needed value of ν is of the order of 10^{-5}. This seems to be not unreasonable, since the observed surface value of ν for RR Lyrae is very much larger ($\nu \sim 1$) and, at the base of the pulsating layers, the magnetic field strength need be only $\sim 10^3$ gauss, which is virtually the same as that observed at the surface. However, during a magnetic cycle, all this magnetic field would have to be annihilated in order to achieve a period change of $\delta P/P \sim 10^{-5}$. Alternatively, if a value $\nu \sim 1$ persists throughout the pulsating layers (except perhaps in the strongly convective layers), then a uniform change of the magnetic energy amounting to only one part in $\sim 10^5$ would suffice to account for the observed period changes. This could also be achieved, more locally, by removing all the magnetic energy in a layer of thickness $\Delta r/R \sim 10^{-2}$ lying immediately below the convection zone.

In all these cases, the magnetic field would have to be replenished from some source deeper in the star, since the magnetic energy necessary to feed the magnetic cycles could not be adequately supplied by the turbulent-dynamo mechanism. Interestingly for our purposes, Layzer et al. (1979) have recently suggested a new mechanism to explain the *solar* magnetic cycles: namely, that the bottom of the (weakly magnetic) convection zone interacts rotationally with an underlying zone of strong magnetic field, so that local torsional oscillations release magnetic flux upward. The details of this theory, however, have yet to be worked out.

It is, nevertheless, still remotely possible that the turbulent-dynamo mechanism could give rise to the observed period changes in RR Lyrae stars, provided that the *radius changes* $\delta R/R$ which are induced by the magnetic and associated convective variations attain a value as large as $\sim 10^{-5}$. In the case of the sun we know only that $\delta R/R < 10^{-4}$. If this limit is typical of RR Lyrae stars, we would expect $\delta P/P < 10^{-4}$. Thus, all we can realistically claim at the present time is that our hypothesis linking period changes with magnetic cycles leads to not unreasonable magnitudes of the various quantities involved, even if the origin of these cycles is not understood.

The time scale of the period changes is our last concern. The fact that the observed Blazhko effect in RR Lyrae stars is subject to large, sudden changes allows us to infer that abrupt period changes of either sign, corresponding to the sudden generation or destruction of magnetic field, can also occur. In harmony with this idea is the observation that stars showing a marked Blazhko effect exhibit the largest period changes (Goranskij, Kukarkin, and Samus' 1973). Pursuing this argument further, we can predict that the interval between successive period changes will be of the order of $\sim$ 10 to $\sim 10^2$ yr. The value of $\sim$ 10 yr refers to the ordinary magnetic cycle of the star. If this cycle is relatively weak, a much longer cycle of $\sim 10^2$ yr (corresponding to the prolonged cessation of the Blazhko effect) may dominate. This latter value seems to agree well with the actual incidence of period changes in RR Lyrae stars.

As an interesting corollary of our results, we would expect to see comparable changes in the sun's pulsation period, if it could be well enough measured. Further observations of both the sun and RR Lyrae stars will be of great importance in pinning down the properties of the magnetic layers that seem to be associated with the observed period changes.

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