OBSERVATIONS OF SECULAR CHANGES IN THE KINEMATIC MODEL OF SS433

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ABSTRACT

In this paper we present evidence that several of the defining parameters of the Kinematic Model for SS433 are not constant but rather exhibit long term systematic changes. Recent data confirm the existence of the previously reported decrease in the precessional period. The value for this period change, when combined with the observed change in the period of the synodic spectral variations, implies that the orbital period is not significantly changing on a time scale less than 1000 years.

In addition we find mounting evidence for a statistically significant (4σ) secular change in the cone angle θ at a rate of about -1.5×10^{-3} deg/day. However, the surprisingly short time scales implied by the observed values of $\dot{P}$ and $\dot{\theta}$ when combined with estimates of the system age suggest the possible existence of detectable higher time derivatives. This view is supported by the most recent data which suggest a value for $\ddot{P} \sim 10^{-5}$ $(\mathrm{days})^{-1}$. It is possible to understand these secular changes in terms of the motions to be expected from an object exhibiting classical precession in response to an external torque.

INTRODUCTION

In the model we proposed for SS433 (Collins and Newsom 1979; Collins et al. 1980, 1981), a large magnetically-distorted star precesses due to the classical gravitational torque of a companion member in a binary system. Ionized matter escaping from the distorted star reaches high speed as it co-rotates out to a large distance, where the matter becomes compressed and emits the characteristic "moving" spectral lines as it encounters material trapped in the stellar magnetosphere. A consequence of this model was that deviations from the five-parameter kinematic model might be observable in the wavelengths of the moving lines in the form of a 6-day period (Collins et al. 1981).

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Following the discovery that this period is indeed present in the moving lines (Newsom and Collins 1981), we searched for other periodic or secular deviations from the kinematic model. By the end of the 1980 observing season, we were surprised to find that the precessional "164-day" period had been decreasing at the remarkably rapid rate of about 1% (Collins and Newsom 1981). It should be noted that Ciatti et al. (1981) also suggested the possibility that the period was decreasing.

This result has proven to be controversial. Following our initial announcement (Collins and Newsom 1980), Margon (1980) concluded that, if the period is decreasing, the rate of decrease is not greater than 0.4% at the 95% confidence level. If our value is confirmed and if the change would continue at this rate, the period would reach zero in half a century. Yet the length of the X-ray jets (Seward et al. 1980) and the presence of the radio "lobes" in W 50 (Geldzahler et al. 1980) imply that high-speed jets (if not the moving lines) have been in existence for at least 10^3 years. Unless we are seeing the final stages of a long-lasting phenomenon, the rate of change of the period would itself be expected to decrease. To confirm the large value of $\dot{P}$ and search for higher-order derivatives in the period, plus secular changes in other parameters of the system that may accompany the period change, we have continued our analysis of the wavelength data. Since some of these parameters have been found to be subject to change, the model parameters are valid only for a specific epoch. For this study this epoch is JD 2444167.5.

OBSERVATIONS AND ANALYSIS

Most of the Doppler shifts used in our analysis are listed in Collins and Newsom (1981) and Wagner et al. (1981). The sources of data and number of data points from each source are as follows: Grandi (1980) 134; Blair (1981) 111; Koski et al. (1980) 36; Crampton (1980) 35; Ohio State University (Newsom et al. 1980; Wagner et al. 1980; Peterson and Crenshaw 1981; Wagner et al. 1981) 27; Liebert et al. (1979) 6; Leibowtz and Mazeh (1979) 5; Ford (1981) 4; Liller (1979) 2; Seaquist et al. (1979) 2; Seaquist (1979) 1. Our 1981 data are all more compatible with a large negative $\dot{P}$ than with a constant period. However, final confirmation that $\dot{P}$ is indeed large and negative came from observations during five nights in June 1981 obtained at the McGraw-Hill Observatory and kindly provided to us by Blair (1981). With these data included, the best current value of $\dot{P}$ is $-0.009 \pm .001$ days/day, as shown by the solid line in Figure 1. More indirect support for the decrease in the precessional period was provided by the observations of Wagner et al. (1981) showing that the 6 day period was also decreasing. Since the 6 day period represents half the synodic period derived from the 13.1-day orbital period and the 164-day precessional period, a change in the precessional period would cause a change in the 6 day period. The rate of change observed in the 6 day period, $-(3.0 \pm 1.1) \times 10^{-5}$ days/day, is very close to the value expected if the orbital period has not changed but the precessional period is decreasing at the rate we had previously found. The change in the precession thus does not appear to result from orbital changes in the binary.

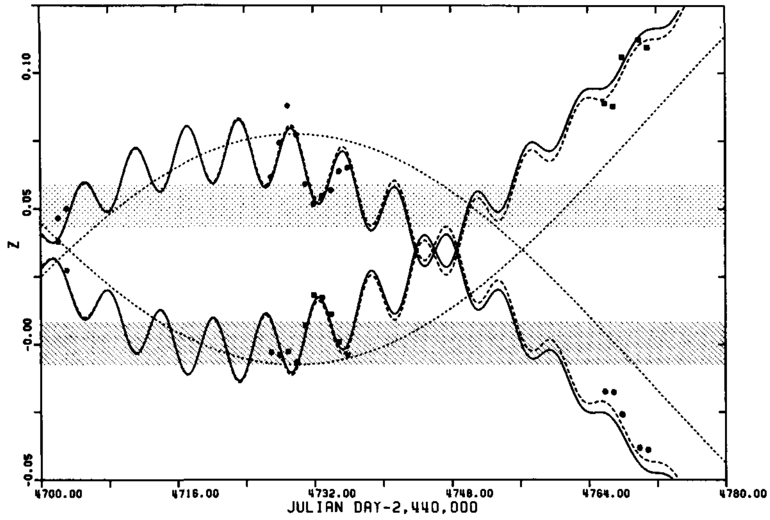

Fig 1. Doppler shift vs time for J.D. 2444700-4780. The solid line includes first derivatives of both the 6 and 164-day periods, while the dashed line also includes the second derivative of the 164-day period. The dotted line is the ephemeris of Margon (1980) which has a constant 164-day period. The ten data points on the right are from Blair (1981) and provide a crucial test of changes in the 164-day period. Shaded areas designate wavelengths at which moving H-α lines are blended with unshifted H-α or atmospheric absorption bands.

When we include the second derivative of the precessional period in our fit to the data, a positive value emerges, as would be expected from the fact that, as more recent data have been added to our fit, the magnitude of $\dot{P}$ has steadily decreased. The presently-available span of observations is not yet adequate to confirm that $\ddot{P}$ is statistically significant, but observations during November, 1981 will hopefully resolve this question. Our best fit, with $\ddot{P} = 1.2 \times 10^{-5}$, is shown as the dashed line in Figure 1. For comparison, the ephemeris of Margon (1980) is shown as a dotted line.

If we regard the angle of inclination of the system as constant, then the two remaining variables in the five-parameter fit subject to secular variation are the cone angle θ and the speed of the beams (represented here by the relativistic time dilation factor, γ). When a first-order expansion of these two variables was included in the

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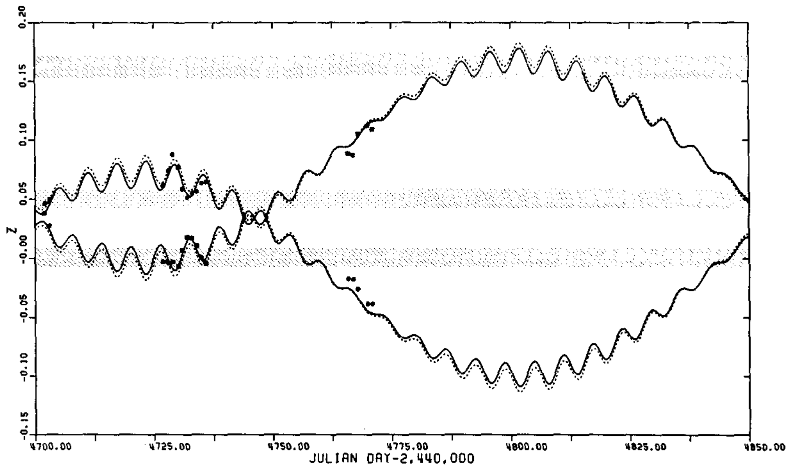

Fig. 2. Doppler shift vs time during spring and summer 1981. First derivatives of both the 6 and 164-day periods are included in both the dotted and solid lines, while the solid line also includes the first derivative in the cone angle θ.

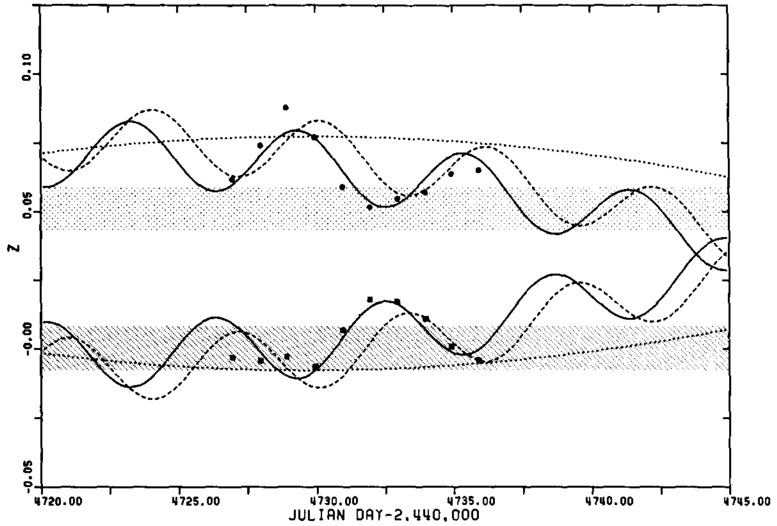

Fig. 3. Doppler shift vs time for J. D. 2444720-4745. The solid and dashed lines both include the first derivative of the 164-day period, while the solid line also includes the first derivative in the 6-day period and cone angle θ. The dotted line is the ephemeris of Margon (1980).

analysis, a remarkably large value of $\dot{\theta}$ was found, amounting to $-(1.5 \pm 0.5) \times 10^{-3}$ degrees/day. During the course of spectroscopic monitoring of SS433, the cone angle has decreased by somewhat less than 2°, resulting in a small but steady decrease in the amplitude of the radial velocity curve. Figure 2 shows a recent cycle with and without including the variation in θ as shown as solid and dotted lines respectively. The combined effects of $\dot{\theta}$ and the decrease in the 6 day period are illustrated in Figure 3 by the solid line. The dashed line shows the best fit to the data if these two effects are excluded, and the fit is considerably poorer. The dotted line is the ephemeris of Margon (1980).

In the midst of these changes, however, the value of γ appears unchanged. Our best fit to $\dot{\gamma}$ is $(0.6 \pm 1.2) \times 10^{-6}$/day. This result implies that there are no <u>secular</u> changes in the speed of the emitting gas greater than 2 km/s/day.

If we assume that the decrease in the cone angle derived from motions of the emitting regions is equal to a change in the orientation of the rotation axis about a precession axis (a plausible but not well-established assumption), then the discoveries reported above can be used to help understand the dynamics in the binary system that appears to drive the high-speed beams.

SOME IMPLICATIONS OF THE SECULAR CHANGES OF THE SYSTEM PARAMETERS

One of the hallmarks of geodetic precession is that for most plausible objects, the direction of the precession is opposite that of the orbital motion. If this is indeed the case, any phenomena resulting from the 'beating' of the orbital period with the long period will produce phenomena with a synodic period less than the orbital period. On this basis Collins *et al.* (1981) suggested that a short period fluctuation exhibiting half the synodic period might be present in the moving line spectra and that if the precession were indeed retrograde, the observed period should be 6 days. The discovery of periodic variations exhibiting a period of 6.06 days (Newsom and Collins 1981) we take as confirmation of the retrograde nature of the precession.

Let us now investigate the extent to which the observed secular changes are consistent with the picture of a geodetically precessing object. Collins *et al.* (1981) have shown that under a wide variety of circumstances the precessional frequency ω_o and spin frequency ω_z of an object exhibiting both geodetic and forced precession is given by:

$$\omega_o^2 \cos\theta - (I_z\, \omega_z\, \omega_o / I_x) + 3\, V_o \cos\theta / I_x = 0 \,, \qquad (1)$$

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where θ is cone angle of the precession and V_o is the perturbing potential resulting from the presence of the companion. The perturbing potential is:

$$V_o = -\omega_b^2 \; \mu \; (I_z - I_x)/2 \tag{2}$$

where ω_b is the angular frequency of the binary motion, μ is the reduced mass of the system and I_z and I_x are the moments of inertia of the precessing object about the body axis and an orthogonal axis respectively. It is worth noting that for any oblate object $I_z > I_x$ which implies $V_o < 0$.

Equation (1) may be rewritten in terms of the dimensionless parameters r and q so that

$$(1+q) \cos \theta - r = 0 ,$$

where $$q = 3\, V_o/I_x\, \omega_o^2 , \tag{3}$$

and $$r = I_z \; \omega_z/(I_x \; \omega_o) .$$

Although we initially suggested (Collins et al. 1981) that magnetic torques on the system implied by the high velocity mass loss should reduce ω_z to zero, it is clear that tidal acceleration by the secondary would tend to oppose this result. Thus it is not unreasonable to suspect that ω_z, although small, may be variable. Such variation would result in a secular change in both ω_o and θ.

Just as it is clear that equations 3 cannot uniquely specify r and q, so it is clear that time derivatives of equations 3 which describe the relationship between the secular changes cannot yield a unique result. The additional physics implying those changes is not included in the equilibrium model giving rise to equations 3. Nevertheless, the time derivatives of equations 3 do place a constraint on the angular spin and its rate of change. Thus

$$\left(\frac{\dot{\omega}_z}{\omega_z}\right)_{t_o} = \left(\frac{\dot{\omega}_o}{\omega_o}\right)_{t_o} \left[\frac{2 \cos \theta}{r} - 1\right]_{t_o} - (\dot{\theta} \;\tan \theta)_{t_o} , \tag{4}$$

where t_o represents the epoch for which the system parameters have been determined.

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If $(\dot{\omega}_z/\omega_z) < 0$, the precessing object is currently losing spin and we would expect $(\dot{\omega}_o/\omega_o) > 0$. The constraint imposed on r for this to be the case is

$$\frac{2\cos\theta}{r} < 1 + (\dot{\theta}\ \tan\theta)/(\dot{\omega}_o/\omega_o) \ . \qquad (5)$$

For the observed values of θ, $\dot{\theta}$, P_o and $\dot{P}_o$ (hence ω_o and $\dot{\omega}_o$) and the definition of r, equation 5 would imply that

$$\frac{I_x\omega_o}{I_z\ \omega_z} < 0.47 \ . \qquad (6)$$

Since the precession is retrograde (i.e. $\omega_o < 0$), any prograde spin $(\omega_z > 0)$ is compatible with equation 6. Thus the observed secular changes are consistent with a geodetically precessing object exhibiting a small amount of prograde rotation which is decreasing at the moment. This decrease leads to an increase in the precession frequency and a decrease in the magnitude of the cone angle as the external torque attempts to align the body axis of the object with the orbital axis.

Admittedly the above interpretation, at this point, is not unique but it is consistent and suggestive. For instance one can explore further aspects of the dynamics of the system for additional constraints on q and r. Our preliminary investigations indicate indeed that such additional constraints do exist. We have found (Collins & Newsom 1982) that the object should exhibit small amplitude nutational variations in the cone angle with a period very roughly of the order of 100 days. Determination of this period, for which we feel some evidence already exists, would enable a unique determination of q, r and $\dot{r}$.

Finally it is worth noting the effect that the dynamical constraints on q and r have on the nature of the precessing object itself. If the object is rapidly spinning (i.e., $\omega_z >> \omega_o$), then it is clear from the definition of r that r >> 1. Thus equation 4 becomes

$$\left(\frac{\dot{\omega}_z}{\omega_z}\right)_{t_o} = -\left[\frac{\dot{\omega}_o}{\omega_o} + (\dot{\theta}\ \tan\theta)\right]_{t_o} \ . \qquad (7)$$

For the measured values of $\dot{P}_o$ and $\dot{\theta}$ we can conclude that $(\dot{\omega}_z/\omega_z)_{t_o} \sim -4.9 \times 10^{-5}$ day^{-1} $\lesssim 0$ and the object is spinning down. Thus the observed secular changes require that any rapidly spinning object subjected to forced geodetic precession is undergoing a loss of spin regardless of the direction of rotation.

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It seems likely that any disk model for the precessing object will require $\omega_z > \omega_b >> \omega_o$. Thus it would appear that any disk model will have to incorporate a physical mechanism which allows the disk to substantially slow down (and probably later speed up). Within the framework of standard disk models this would seem very difficult to accomplish. Although one may argue that the classical dynamics approach exhibited here is inapplicable to disks, the fact remains that the observed secular changes must be incorporated into any model of this system and they are natural consequences of the classical description.

Additional observation of this object should serve to further quantify the secular changes we have described here as well as establish the existence of nutation and period acceleration (i.e. $\ddot{P}_o$). Within the classical picture, we can expect such quantification to uniquely specify q and r and thereby illuminate the specific nature of the binary. It seems reasonable to suggest that, although this may well be the most enigmatic object to be discovered in twenty years, we can understand it and thereby learn something of the evolution of a truly unusual binary system.

We would like to thank the observers who provided us directly with data. Particular thanks are due W. P. Blair, whose results from June 1981 were definitive in establishing the values quoted in this paper. We also would like to thank Z. Kopal for suggesting we make this contribution. Since the original preparation of this work, Margon has reversed his position on the value of $\dot{P}$ (Margon 1980), and he now finds a value (Margon et al. 1981) that confirms our original announcement (Collins and Newsom 1980) and is in precise agreement with the value quoted here.

REFERENCES

Blair, W.P.: 1981. Private communication.

Ciatti, F., Mammano, A., and Vittone, A.: 1981, Vistas in Astron. (in press).

Collins, G. W., II, and Newsom, G. H.: 1979, Nature 280, pp. 474-475.

Collins, G. W., II, and Newsom, G. H.: 1980, IAU Circ. No. 3547.

Collins, G. W., II, Newsom, G. H., and Boyd, R. N.: 1980 in M. Plavec, D. M. Popper, and R. K. Ulrich (eds.), "Close Binary Stars: Observations and Interpretation", IAU Symp. 88, pp. 375-379.

Collins, G. W., II, and Newsom, G. H.: 1982, Astrophys. Space Sci. 81, pp. 199-208.

Collins, G. W., II, Newsom, G. H., and Boyd, R. N.: 1981, Astrophys. Space Sci 76, pp. 417-440.

Collins, G. W., II, and Newsom, G. H.: 1982, in preparation.

Crampton, D.: 1980. Private communication.

Ford, H.: 1981. Private communication.

Geldzahler, B. J., Pauls, T., and Salter, C. J.: 1980, Astron. Astrophys., 84, 237-244.

Grandi, S. A.: 1980. Private communication.

Koski, A., Burbidge, E. M., and Smith, H. E.: 1980. Private communication.

Leibowitz, E. M., and Mazeh, T.: 1979, IAU Circ. No. 3367.

Liebert, J., Angel, J. R. P., Hege, E. K., Martin, P. G., and Blair, W. P.: 1979, Nature 279, pp. 384-387.

Liller, W.: 1979. Private communication.

Margon, B.: 1980. Paper delivered at the Tenth Texas Symposium on Relativistic Astrophys, December, Baltimore, Maryland.

Margon, B., Anderson, S., Grandi, S., and Downes, R.: 1981, IAU Circ. No. 3626.

Newsom, G. H., Jenkner, H., and Wagner, R. M.: 1980, Astron. J. 85, 1229-1231.

Newsom, G. H., and Collins, G. W., II: 1981, Astron. J. 86, 1250-1258.

Peterson, B. M., and Crenshaw, D. M.: 1981. Private communication.

Seaquist, E. R.: 1979. Private communication.

Seaquist, E. R., Garrison, R. F., Gregory, P. C., Taylor, A. R., and Crane, P. C.: 1979, Astron. J. 84, pp. 1037-1041.

Seward, F., Grindlay, J., Seaquist, E., and Gilmore, W.: 1980, Nature, 287, pp. 806-808.

Wagner, R. M., Byard, P. L., Foltz, C. B., and Peterson, B. M.: 1980. Private communication.

Wagner, R. M., Newsom, G. H., Foltz, C. B., and Byard, P. L.: 1981, Astron. J. (in press).