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High-speed photometry of the Intermediate Polar V1223 Sgr

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Summary. We report and analyse 104 hr of photometry of the Intermediate Polar V1223 Sgr at 5 and 10 s time resolution obtained during 1981 and 1982. From the various periodic brightness modulations we derive an orbital period of 0.140239 day, a rotation period of the primary of 794.380 s and an orbital sideband of 849.8 s. The last is only intermittently present.

The 794 and 850 s oscillations are in phase coherence at maximum of the orbital brightness modulation. The contrast with AO Psc (H 2252 – 035), where phase coherence occurs at orbital brightness minimum, leads to a model in which the 794 s modulation results from reprocessing of X-ray beam from the axisymmetric parts of the accretion disc.

The high-speed brightness variations of V1223 Sgr possess two unusual properties: an intrinsic 'scintillation' in which the system may increase or decrease its brightness by 10–20 per cent on time-scales ~100 s, and excess power in the frequency range 0.04–0.08 Hz when compared with other active cataclysmic variables. The Intermediate Polar AO Psc shows similar behaviour.

1 Introduction

On the basis of accurate *HEAO-A3* and *Ariel 5* positions, Steiner *et al.* (1980a) identified the X-ray source 4U 1849 – 31 with the thirteenth magnitude irregular variable V1223 Sgr. Spectra showed emission lines characteristic of a cataclysmic variable star. Steiner, Jablowski & Busko (1980b) confirmed that the *UBV* colours are similar to those of such a star and additionally discovered brightness variations with a period of 13.2 min and amplitude ~10 per cent. They pointed out the similarity of V1223 Sgr to the X-ray source H2252 – 035 (AO Psc) (Patterson & Price 1981; Warner, O'Donoghue & Fairall 1981). The general characteristics of V1223 Sgr place it in the class of objects now known as Intermediate Polars (Warner 1982). These are cataclysmic binaries in which the white dwarf primary is thought to have a significant magnetic field, not strong enough to produce synchronous rotation as in the Polars (AM Her stars: Kruszewski 1978), but sufficient to dominate the accretion flow from the inner edge of the accretion disc, leading to an accretion column close to the surface of the white dwarf. Rotation of the latter sweeps a beam of X-rays around the system, which may be intercepted and degraded by the accretion disc and secondary star.

To date, the only studies of V1223 Sgr are the detailed report of the observations by Steiner *et al.* (1981), which include a small amount of optical photometry, and the *IUE* ultraviolet observations by Bonnet-Bidaud, Mouchet & Motch (1982). We report here the results of photometric observations of V1223 Sgr covering the 1981 and 1982 observing seasons.

2 Observations

All observations were made on the 30- and 40-in reflectors at the Sutherland site of the South African Astronomical Observatory using the high-speed photometer belonging to the University of Cape Town (which latter is similar to that described by Warner 1971). In order to maximize the photon detection rate, no filters were used. During the 1981 observing season an S-11 response 56 DVP photomultiplier was used; this was replaced in 1982 by an S-20 RCA 8644.

The log of our observations, associated into weeks, is given in Table 1. A total of 104 hr of photometry is listed.

Table 1. Photometric observations of V1223 Sgr.

Week	Run no.	Date	Telescope (in)	$JD_\odot$ (start) 2440000+	Integration time (s)	No. of integrations
1	S2848	1981 March 29	30	4692.63909	5	349
	S2853	March 30	30	4693.54031	5	1749
	S2856	March 31	30	4694.55936	5	1629
2	S2862	April 30	30	4725.47935	10	1610
	S2865	May 3	30	4727.64024	5	429
3	S2868	May 26	30	4751.49152	10	670
	S2875	May 31	30	4755.57219	10	977
	S2876	May 31	30	4756.46442	10	519
	S2880	June 1	30	4757.40557	10	2399
4	S2884	June 3	30	4758.57797	10	819
	S2891	June 9	30	4764.51887	10	1467
5	S2893	June 30	40	4786.43560	10	898
	S2896	July 1	40	4787.41817	10	1999
	S2899	July 2	40	4788.46611	10	809
	S2906	July 4	40	4790.43536	10	1694
	S2909	July 5	40	4791.34169	10	929
6	S2964	1982 March 24	30	5052.56523	10	716
	S2968	March 25	30	5053.58713	10	565
	S2976	March 29	30	5057.59708	10	523
7	S2985	May 19	30	5108.52905	10	708
	S2987	May 20	30	5109.59911	10	767
	S2988	May 21	30	5110.46711	10	1784
	S2991	May 22	30	5112.40875	10	2363
	S2993	May 23	30	5113.40416	10	2398
8	S2995	May 25	40	5115.44762	10	1019
	S3000	May 28	40	5117.55086	5	2178
	S3004	May 30	40	5119.53878	5	2369
	S3007	May 31	40	5120.49287	5	1617
9	S3016	June 22	30	5143.35848	10	2610
	S3021	June 27	30	5148.38094	10	251
	S3022	June 28	30	5149.41849	10	1729
10	S3023	July 24	30	5175.30437	10	2126

3 Long time-scale changes

Examination of the Harvard plate collection has shown (Belserene 1981) that V1223 Sgr has a persistent high state, interrupted over the period covered by the plate material, by five reductions in brightness of two to three magnitudes and a 12 yr interval of irregular variations at intermediate brightness.

Four of our longest light curves are shown in Fig. 1. Three of these show significant linear trends during observation. As the star passed through the zenith near the centre of each of these runs, any error in our adopted 0.40 mag extinction coefficient cannot be held responsible. It is evident, therefore, that V1223 Sgr has slow variations in brightness of ~ 15 per cent on a time-scale ~ 1 day.

4 The orbital period

V1223 Sgr also shows a low amplitude modulation in brightness with a time-scale ~ 3 hr (Fig. 1). This is not always conspicuous, which prevents simple cycle count test for periodicity. By analogy with AO Psc, we expect to see just such a modulation arising from the changing aspect of the X-ray illuminated secondary (or hotspot: Warner 1983) during orbital revolution. In the absence of a spectroscopic orbital period we must depend entirely on analysis of the photometry to provide the orbital period.

A Fourier analysis was performed, using the technique described in the Appendix of O'Donoghue & Warner (1982), of all of our light curves. In order not to dilute the orbital modulation by night to night variations in mean brightness, it was necessary to remove mean light and first order trends from each night's observations. The amplitude spectrum of our complete data set is shown in Fig. 2. The narrowness of the spikes in the 'window pattern' near 8×10^{-5} Hz is consistent with the presence of a coherent periodic modulation with a mean amplitude of 3.0 per cent. There is, however, an ambiguity in the period resulting from a one day alias. The period is either 3.366 or 2.952 hr. Fortunately this alias can be broken by appeal to observations made at observatories with longitudes very different from that of Sutherland (see below), thus providing phase measurements at times unobservable at the latter. These favour the first period, which enables us to determine the following ephemeris for light maximum, based entirely on the observations listed in Table 1:

$$JD_{\odot}(\max) = 2444749.9866 + 0.140239E \text{ day} \quad (1)$$

where E is the number of cycles elapsed.

The other observations available to us are (a) fig. 3 of Steiner *et al.* (1981): our ephemeris predicts a maximum 171 min after the zero of their abscissa, in agreement with their observation, and (b) a minimum at JD 2445128.137 ± 0.002 and a maximum at JD 2445132.279 ± 0.014 reported by Dr D. Watts (personal communication) from observations on the Anglo-Australian telescope. Our ephemeris predicts a minimum at $JD_{\odot}$2445128.140 and a maximum at $JD_{\odot}$2445132.278 respectively.

5 The 13-min period

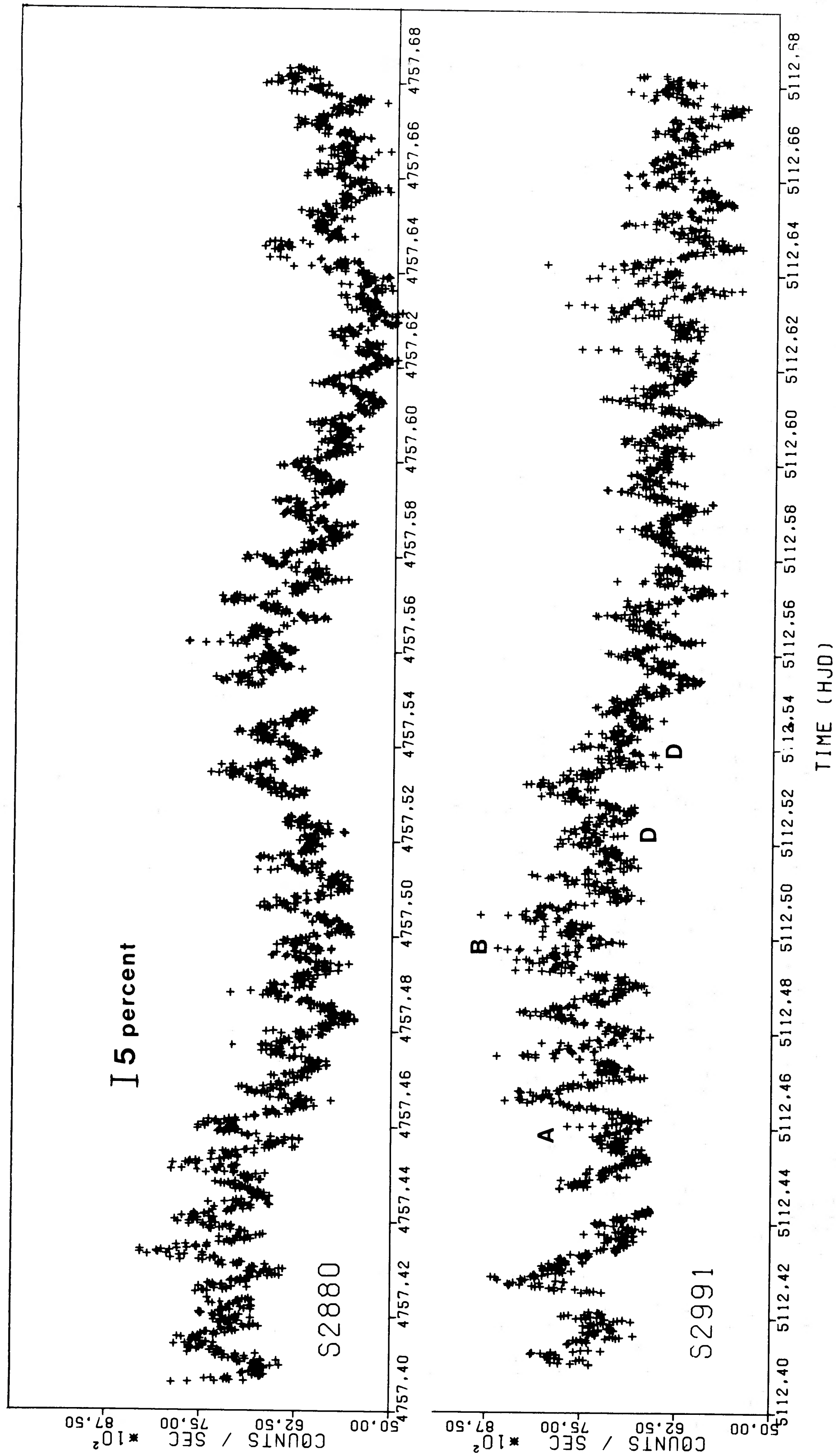
A Fourier amplitude spectrum of the de-trended observational data set in the vicinity of the 13.2 min period is shown in Fig. 3. From this we deduce the following ephemeris:

$$JD_{\odot}(\max) = 2444750.00404 + 0.00919421E \text{ day}. \quad (2)$$

Our period is consistent with that

(0.009194 ± 0.000001 day)

±4



(a)

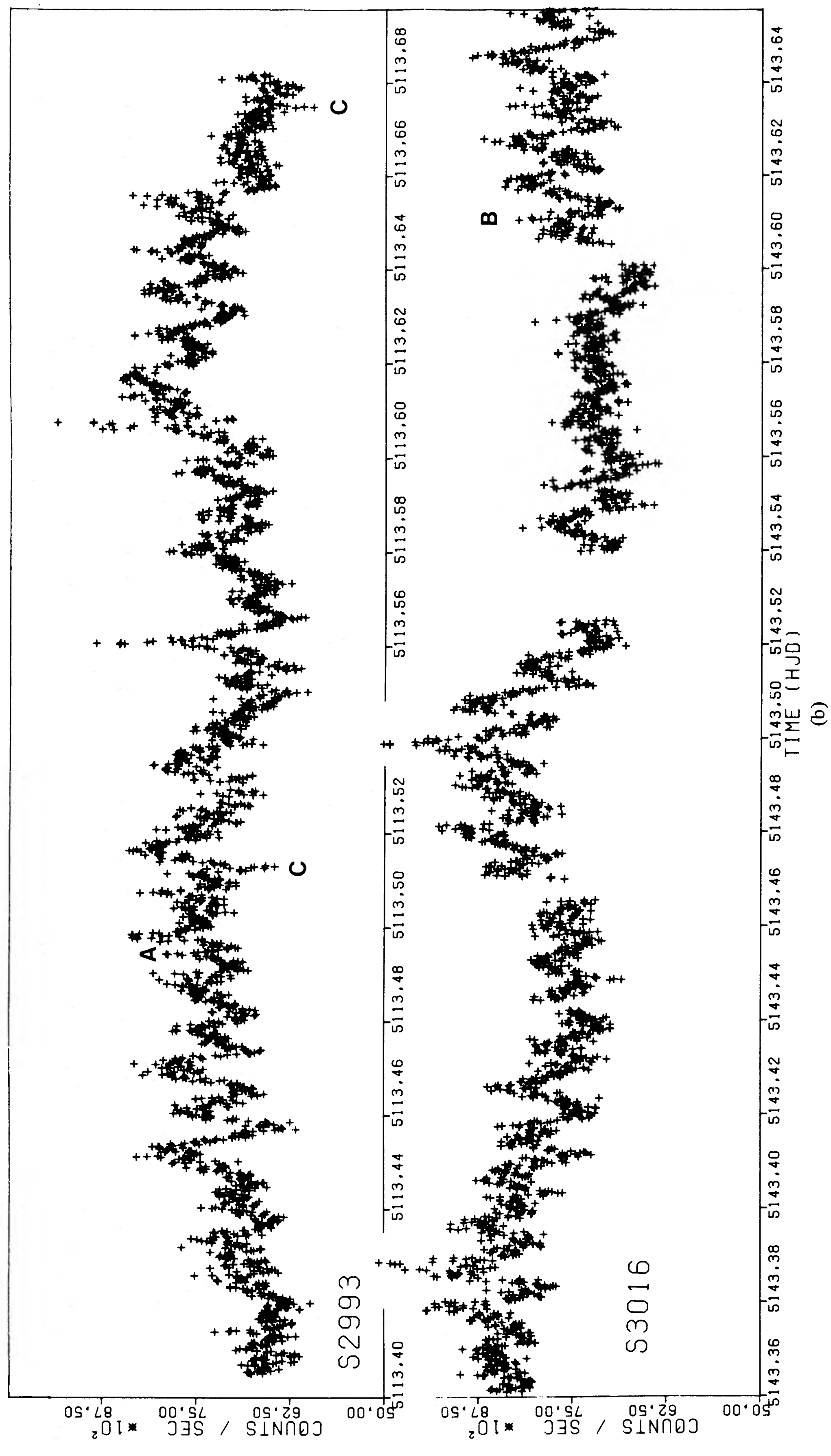


Figure 1. (a, b) Light curves of V1223 Sgr. Each point is a 10 s integration. The abscissae are JD$_{\odot}$2440000+.

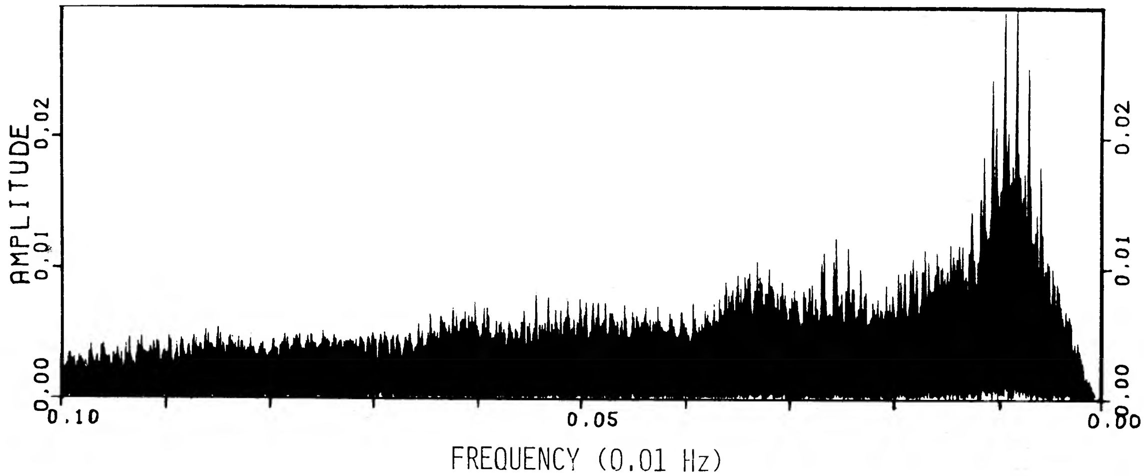


Figure 2. Fourier amplitude spectrum (low frequency end) of 1981–82 data.

given by Steiner *et al.* (1981). Using their epoch from 1980 September provides an improved period of

0.009194215 (= 794.380 s ± 0.002 s).
±5

Fourier spectra were also calculated for the 1981 and 1982 seasons separately. The resulting periods, 794.390 and 794.381 s respectively, do not differ by more than our estimated errors of determination.

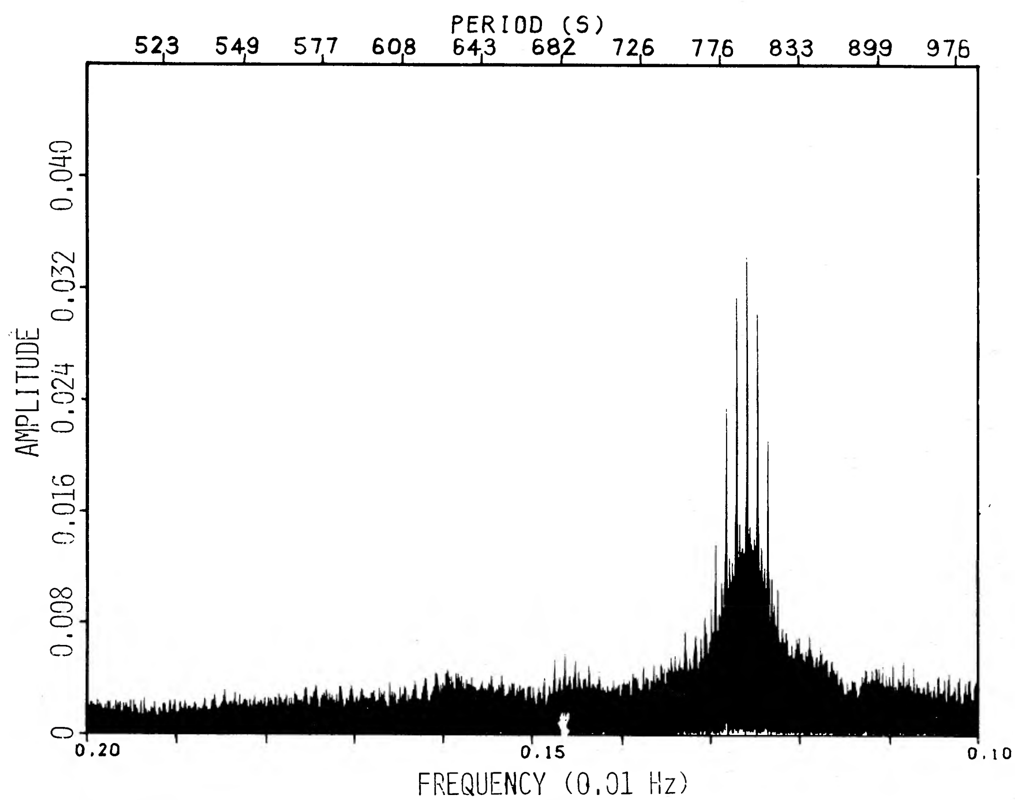


Figure 3. Fourier amplitude spectrum in vicinity of 794 s oscillation.

The mean amplitude of the 13.2 min modulation is 3.0 per cent (Fig. 3). However, as seen in Fig. 1, individual cycles may have amplitudes up to 15 per cent. In amplitude spectra of the total data set there are no detections (with an upper limit of 0.2 per cent in amplitude) of the first harmonic or of the subharmonic (upper limit 0.5 per cent) to the 13.2 min periodicity.

6 The orbital sideband

Photometric observations of AO Psc (Warner & O'Donoghue 1980; Warner *et al.* 1981) showed the presence of a weak 805 s periodicity as well as the dominant 859 s period. The first of these periods is the same as that seen in the X-ray emission (White & Marshall 1981) and leads to a model in which the 859 optical pulse is the 805 s X-ray pulse reprocessed off of a structure (the secondary or the hotspot) rotating at the orbital frequency. The 805 s optical pulse arises either on the surface of the primary or from reprocessing in the axially symmetric parts of the accretion disc surrounding the primary.

Unlike AO Psc, an orbital sideband is not immediately obvious in the amplitude spectra of V1223 Sgr. Pre-whitening our data, by subtraction of the mean 13.2 min sinusoid, leads to a Fourier spectrum with no very significant peaks. Using the 1982 observations alone, however, there is one peak that stands just above the noise, but which we would not consider significant were it not for the period that it represents: 849.8 ± 0.5 s. The periods determined in Section 3 and 4 predict that an orbital sideband could occur either at 850.11 or 745.50 s, dependent on whether the 794 s period is the direct pulse from the primary or the reprocessed pulse from, e.g. the secondary. The coincidence of our observed low amplitude periodicity and one of the possible sideband periods encouraged us to investigate this oscillation in more detail.

Examination of Fourier spectra of individual nights' observations, for all runs where the duration of observations was long enough clearly to resolve the 794 and 850 s periodicities, showed the latter to be strongly present only during week 7 (Table 1). Fourier spectra for the three longest runs and for the week's data as a whole, are shown in Fig. 4. The spectra for individual nights were smoothed by summing the observations into 100 s bins before processing.

As can be seen, on three consecutive nights there is a significant peak near 850 s and the week as a whole shows a similar peak indicating that the individual nights added coherently. Note that on individual nights the noise in the amplitude spectra is such that peaks arising from low amplitude coherent signals may be distorted; this is evident in the orbital sideband peak and is detectable even in the principal (794 s) peak.

In runs S2991 and S2993 the sideband amplitude is nearly half that of the 794 s pulse. The effects of beating between these two oscillations is clearly discernible in Fig. 1: the mean amplitude near the maximum of the orbital modulation is considerably larger than near minimum.

From the pre-whitened amplitude spectrum of the 1982 data we derive the following ephemeris for the orbital sideband:

$$JD_{\odot}(\max) = 2444750.00350 + 0.00983588E \text{ day}. \qquad (3)$$

Although there are indications of the sideband being weakly present in some of the other runs, it is week 7 that contributes predominantly to the derivation of this ephemeris so we advise caution in using it at a time far removed from that week.

Equations (2) and (3) show that the 794 and 850 s oscillations were in phase coincidence at $JD_{\odot}$ 2445113.4807 during run S2993. Equation (1) predicts an orbital maximum at $JD_{\odot}$ 2445113.4861. Therefore phase coherence of the principal oscillation and its orbital

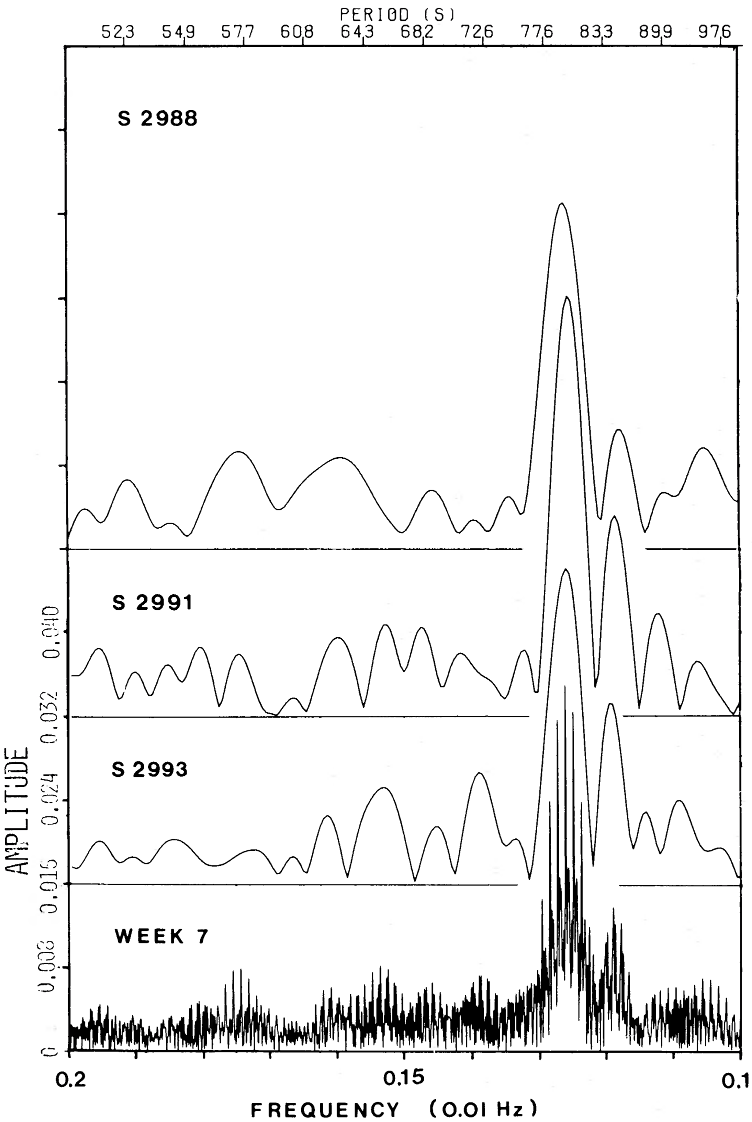


Figure 4. Fourier amplitude spectra of individual nights and for the whole of week 7.

sideband occur 0.0054 day = 0.038 orbital period = 14° of orbital revolution prior to maximum of the orbitally modulated light variation. The uncertainty is ~ ±20°, so *phase coherence and orbital maximum are coincident within observational error.* This contrasts with AO Psc, where phase coherence and orbital *minimum* are coincident (Motch & Pakull 1981). We will discuss the significance of this in Section 9.

Some explanatory comments on the nature of the noise that appears in the amplitude spectra seen in Fig. 4 may be required. V1223 Sgr, as with other cataclysmic variables, shows stochastic variations in brightness on a variety of time-scales. Power spectra of finite data lengths of these stars typically show non-white noise, but with maxima and minima that do not repeat from one observation to the next. Such effects are seen in the spectra of the individual nights shown in Fig. 4. Note that by displaying amplitude spectra, rather than the more usual power spectra (or log power spectra), our illustrations appear to have greater noise (relative to the coherent signal) than the traditional plots. They have the advantage, however, that the amplitudes are directly visible.

The spectrum of week 7 appears to show the presence of low amplitude coherent oscillations in addition to the principal oscillation and its orbital sideband. This, however, is spurious: basically the result of statistics of small numbers. For example, consider the 'window pattern' standing above the background noise at 0.175×10^{-2} Hz in week 7. This is similar in amplitude and location to the broad peak in run S2988. Addition of a large number of other runs would dilute the effect of the bump in S2988, but we are adding together only five nights and it happens that there is a broad hump of power in the same frequency region in the short (and therefore low resolution) run S2985 with about four times the amplitude of that in S2988. As a result, by chance the 0.175×10^{-2} Hz power is preserved at nearly the amplitude seen at S2998.

Addition of a much larger number of runs does indeed result in dilution of this particular excess of power, as can be seen in Fig. 2 where its window pattern is barely above the (much lower) noise.

Unfortunately, true coherent signals will also be diluted if they are present only occasionally. This is why the orbital sideband is hardly apparent in Fig. 2. However, the reality of the orbital sideband is ensured both by its occurrence at the predicted period and its phase coherence (with the principal pulse) at a special phase in the orbital cycle.

7 Scintillation

The light curves of V1223 Sgr seen in Fig. 1 are remarkable for the occasional occurrence of large brightness variations on time-scales 10–100 s. In run S2993, for example, there are two flares in which the star brightened by ~ 20 per cent in under a minute.

On casual inspection, the flares appear to favour maxima of the 13.2 min pulse, but counter-examples may be found: flares marked A occur at minima and B midway through the 13.2 min cycle.

There are also instances of unusually low points, those marked C in S2993 for example, which take the light curve well below the lower envelope of the 13.2 min pulses. Other low regions, less noticeable away from minima of the 13.2 min cycle, also occur: the points marked D in run S2991 for example. These 'anti-flares' lower the light curve by amounts comparable to the increase seen during flares.

This phenomenon, in which both positive and negative rapid brightness changes occur, bears such a strong resemblance to the naked eye twinkling of stars, albeit on a longer time-scale, that the epithet 'scintillation' seems appropriate.

Similar scintillation appears in the light curves of AO Psc (Warner *et al.* 1981) but has not previously been remarked upon.

8 High frequency flickering

All of our light curves of V1223 Sgr possess an underlying scatter that never decreases below a total width of ~ 5 per cent. This is best seen in S2880 (Fig. 1) where intrinsic scintillation least affects the light curve. The detected count rate was ~ 45 000 counts per integration, which would give a $\pm 2\sigma$ band 1.9 per cent wide. Seeing conditions were in general very good (particularly near the zenith) and should not have contributed more than ±0.5 per cent to the scatter. The observed noise, on a time-scale ~ 50 s, is therefore nearly three times that attributable to the observing technique and must originate in the star.

In Fig. 5 a comparison is made between the power spectra of V1223 Sgr and VY Scl. The latter is one of the most active of cataclysmic variables (see the light curve, fig. 1 of Warner & van Citters 1974) and is of similar apparent magnitude to V1223 Sgr. Both stars were observed with 5 s time resolution on the 40-inch reflector at Sutherland. Examples of power spectra of other active cataclysmic variables are those of CN Ori (Warner & Robinson 1972) and DQ Her (Kiplinger & Nather 1975). In VY Scl, CN Ori and DQ Her the excess power at

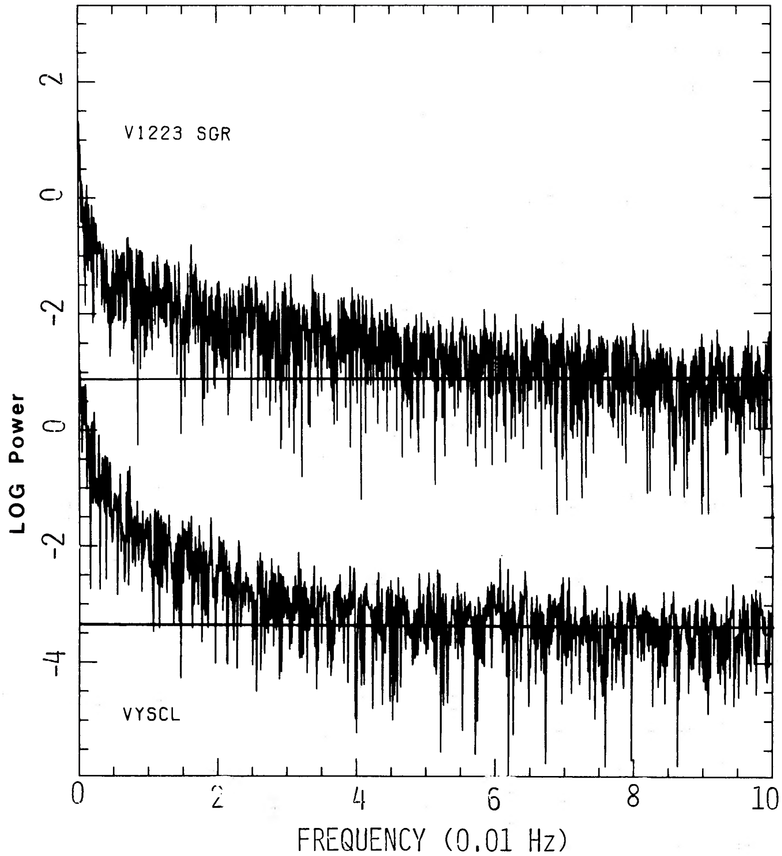


Figure 5. Power spectra of V1223 Sgr and VY Scl.

low frequencies merges into the background noise at ~0.04 Hz; in V1223 Sgr the excess power is evident to ~0.08 Hz. The power spectrum of V1223 Sgr, with its slow decay to high frequencies, is almost identical to that of AO Psc (fig. 4 of Warner *et al.* 1981). In both of these Intermediate Polars, therefore, there is clear evidence of greater activity at high frequencies than in other systems. A comparative study at higher time resolution is required.

9 A phenomenological model

The most striking aspect of V1223 Sgr is its reversal of the behaviour seen in AO Psc. In the latter, rotation of the primary produces an 805 s X-ray modulation, which is detected with low and variable amplitude in the visible (Warner *et al.* 1981; Patterson & Price 1981; Motch & Pakull 1981; Wickramasinghe, Stobie & Bessell 1982), and an orbital sideband at 859 s with large optical amplitude. In V1223 Sgr the roles are reversed; the periods are 794 and 850 s respectively. In addition, the position in orbit of phase coherence between the direct and reprocessed pulses differs by 180° in the two stars. We may account for the different behaviour of the two stars with the following phenomenological model.

In AO Psc the orbital and 859 s modulations arise from X-ray heating of the hotspot (Hassall *et al.* 1981) or secondary (Patterson & Price 1981). The 805 s optical modulation has a spectral gradient which resembles the Rayleigh–Jeans tail of a hot (~10^5 K) blackbody (Motch & Pakull 1981); the source of this emission is probably the X-rays reprocessed by the surface of the white dwarf. We suppose that the disc as a whole is not strongly heated by the rotating X-ray beam. The 805 and 859 s optical pulses will be seen coincident when the orbital reprocessor (i.e. the secondary star or the hotspot) is at inferior conjunction.

In V1223 Sgr, by contrast, we suggest that the X-ray beam is directed so that it principally illuminates the accretion disc, and only a small fraction falls on the orbital reprocessor. (If the X-ray beam arises from the accretion column near a magnetic pole, then in AO Psc the pole is at high latitude whereas in V1223 Sgr it is near the equator). We now have a situation where the dominant optical pulse will come from the axisymmetric parts of the disc. However, as seen from Earth, an asymmetry can arise: if the system is of moderately high inclination then because the disc surface is concave, the back side of the disc projects a larger area than the front. Alternatively, if the inner edge of the disc is above the surface of the primary (as is the case when magnetic fields are strong enough to dominate accretion near the primary), then the dominant reprocessing site can be the inner edge of the disc, which has a strong front–back asymmetry for all inclinations other than 0°. In either case optical modulation at the period of rotation of the primary will have maximum intensity when the X-ray beam is pointing away from the observer. This results, in the case of V1223 Sgr, in phase coherence of the 794 and 850 s oscillations when the orbital reprocessor is at superior conjunction.

After this model had been developed, van Paradijs (1983) reported that the spectral gradients of the 794 and 850 s oscillations in V1223 Sgr (the latter independently discovered by him), are similar to that of the 859 s oscillation in AO Psc. This is in accord with our model if the 794 s oscillation is produced mostly in the outer regions of the disc, so that all three of the above oscillations arise from reprocessing in cool atmospheres, in contrast to the 805 s optical pulse in AO Psc which comes from the hot primary star.

We predict from our model that the X-ray emission from V1223 Sgr will have the same period as, but will differ by 180° in phase from, the 794 s optical oscillation.

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