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Short-Term Optical Variability of HD 153919 = 4U1700-37

by

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ABSTRACT

New optical observations of HD 153919 obtained at La Silla in June 1978 confirm the presence of cyclic short term variations in this object. The derived period is found to be 94.6 min. The analysis of two previous sets of photometric data gives an almost unique value of P = 09.9 min for the 1976 observations of van Paradijs *et al.* (1978), and several possible solutions ranging from 100.2 min to 115.7 min for the 1975 observations of van Genderen and Uiterwaal (1976).

The amplitude of variations is not constant and ranges from 0.02 mag to 0.002 mag or less. There is a strong dependence of the amplitude on the orbital phase, but it varies also on longer time intervals.

There are fairly good evidences for a secular decrease of the period. The derived rate of decrease $\dot{P}/P = -0.03$ years^{-1} is consistent with the rate expected from disk accretion onto a neutron star.

1. Introduction

The X-ray source 4U1700-37 is known to be an eclipsing binary with the 06f supergiant star HD 153919 as the optical counterpart (Jones *et al.* 1973). Previous optical observations of HD 153919 have shown that it is a single-spectrum spectroscopic binary with its orbital period of 3.4 days equal to that derived from the X-ray observations (Thackeray and Walker 1973, van den Heuvel 1973, Hutchings *et al.* 1973, Hensberge *et al.* 1973). Its visual lightcurve displays two shallow minima, occuring around

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the time of the X-ray eclipses and also at times when the X-ray source is in front of the optical component (Penny *et al.* 1973, Jones and Liller 1973).

The X-ray intensity variations present a quite regular feature in the form of a total eclipse. The time of the mid-eclipse is given by the following ephemeris: J. D. $= 2442476.6803 + 3.41180E$ (Branduardi *et al.* 1978). This ephemeris has been used throughout the present paper for calculating the orbital phases. The duration of the totality is 0.9 days or 0.26 of the orbital cycle, and seems to be slightly variable (Jones *et al.* 1973, Mason *et al.* 1976, Branduardi *et al.* 1978). Outside this phase interval the X-ray intensity is highly variable on different time scales, down to a tenth of a second (Jones *et al.* 1973). Mason, Branduardi and Sanford (1976) have noticed that the dominating time scale of variations is one hour, and that these variations are energy independent in the 3.5 — 10.5 keV range.

From observations performed with SAS-3, it was discovered (Matilsky and Jessen 1978, Matilsky, LaSala and Jessen 1978) that the X-ray intensity of 4U1700-37 apparently undergoes 96.8 min periodic variations. It was argued that these periodic variations had not been discovered earlier because of interference with the 94.5 min sideral and 101 min synodic (South Atlantic anomaly) periods of the satellite.

The presence of gaps in the observational data, spaced by 94.5 and 101 min, was suggested also as a cause of the apparent periodic variations by Hammerschlag-Hensberge, Henrichs and Shaham (1979). They argued that relatively slow X-ray variations such as a single smooth flare lasting only 0.6 days when seen through the observational window, may simulate the 96.8 min periodic variations. However, they clearly oversimplified the slow X-ray variations and ignored the short period variations actually seen in the unprocessed observational data (Mason *et al.* 1976 Fig. 1, Matilsky *et al.* 1978 Fig. 1) and therefore their arguments are not very persuasive.

Kemp and Wolstencroft (1973) have reported from their measurements of HD 153919 the presence of circular polarization in the H_β emission line, fluctuating up to 0.15 % on a short time scale. The sign of the polarization was found to change in less than 10 minutes, but when averaging these measurements over time intervals between one and three hours the resulting polarizations are much smaller. The fluctuating polarizations show a clear dependence on the orbital phase, with polarizations which are significantly larger than the measuring errors occuring only during the orbital phase 0.4 — 0.8. Other polarimetric observations have not yet effectively disproved the presence of such a fluctuating circular polarization. Photographic measurements may not have sufficiently high time-resolution (Hensberge *et al.* 1973), while the photoelectric measurements of Angel *et al.* (1973) were made at orbital phases when also Kemp and Wolstencroft found zero polarization.

From photometric observations in the filter *V*, van Genderen and Uiterwaal (1976) have concluded that during the rising branch of the primary optical minimum HD 153919 shows short term fluctuations with a time scale of one hour.

Following the discovery of the X-ray pulsations (Matilsky and Jessen 1978) Kruszewski (1978) confirmed the presence of small amplitude variations within a time scale consistent with the X-ray period, from the analysis of two previous sets of visual photometry (van Paradijs *et al.* 1978, van Genderen and Uiterwaal 1976). The amplitude appears the largest up to 0.02 mag, only in the limited range 0.44-0.59 of the orbital phases. Consequently there are several possible values for the period which can be fitted to the observations.

Van Genderen has monitored HD 153919 in the *V* spectral band during an 8 hour run on June 29/30, 1978. This run covered the orbital phases from 0.46 to 0.57 but no short term variations with an amplitude $0^{\mathrm{m}}.01$ or larger (Hammerschlag-Hensberge *et al.* 1979) could be detected.

New photometric observations have been obtained at ESO Observatory (La Silla). The observing run performed on June 15, 1978 during the phase interval 0.40-0.48 resulted in detecting cyclic variations with an apparent period of 95 ± 3 min and an amplitude reaching 0.01 mag in the *V* filter (Surdej 1978). Additional observations recorded through an interferential filter centered on the He II 4686 emission line display similar variations but the latter are characterized by the presence of two maxima and two minima during a single pulsation cycle. The variations are of smaller amplitude or absent in the *B* and *U* filters.

In this paper the photometric observations made at La Silla are presented and discussed in more details. We also applied the Fourier analysis to existing photometric material in order to investigate the reality of the claimed optical pulsations.

2. New Observations

A stimulus for making a new set of photometric observations was the suggestion (Kruszewski 1978) that the optical brightness of HD 153919 shows small periodic variations compatible with the period of the claimed X-ray pulsations (Matilsky and Jessen 1978, Matilsky *et al.* 1978). It was planned to perform these observations during the most favorable orbital phase interval, namely 0.44-0.59.

Table 1
New observations of HD 153919

JD Hel. 2443600+	Δm	JD Hel. 2443600+	Δm	JD Hel. 2443600+	Δm	JD Hel. 2443600+	Δm	JD Hel. 2443600+	Δm
filter U		filter U		filter U		filter B		filter B	
48.7880	-1.319	54.8600	-1.420	75.7733	-1.385	48.8333	-0.613	75.6047	-0.670
.7913	-1.318	54.8649	-1.412	.7751	-1.382	.8365	-0.615	.6096	-0.672
.7972	-1.321	75.5763	-1.409	.7801	-1.384	.8414	-0.614	.6112	-0.674
.8001	-1.322	.5779	-1.403	.7818	-1.382	.8447	-0.613	.6128	-0.678
.8031	-1.322	.5796	-1.401	.7866	-1.382	.8474	-0.609	.6178	-0.677
.8065	-1.326	.5844	-1.407	.7894	-1.376	.8508	-0.615	.6195	-0.680
.8098	-1.325	.5861	-1.407	.7921	-1.381	.8561	-0.616	.6212	-0.673
.8126	-1.324	.5877	-1.399	.7986	-1.380	.8605	-0.608	.6259	-0.675
.8159	-1.322	.5930	-1.406	.8004	-1.377	.8643	-0.613	.6276	-0.677
.8204	-1.326	.5946	-1.403	.8021	-1.378	.8675	-0.616	.6294	-0.677
.8237	-1.322	.5963	-1.403	.8069	-1.381	.8706	-0.615	.6341	-0.676
.8268	-1.318	.6011	-1.403	.8087	-1.376	.8751	-0.615	.6359	-0.677
.8299	-1.320	.6029	-1.405	.8104	-1.376	.8786	-0.620	.6376	-0.675
.8331	-1.321	.6044	-1.402	.8152	-1.380	.8817	-0.619	.6425	-0.674
.8363	-1.318	.6092	-1.404	.8170	-1.374	.8849	-0.618	.6441	-0.669
.8412	-1.319	.6109	-1.402	.8187	-1.378	.8891	-0.617	.6458	-0.667
.8445	-1.313	.6126	-1.405	.8237	-1.373	.8923	-0.619	.6504	-0.670
.8472	-1.312	.6175	-1.398	.8254	-1.371	.8953	-0.621	.6522	-0.671
.8505	-1.310	.6192	-1.403	.8271	-1.368	.8984	-0.617	.6539	-0.674
.8560	-1.317	.6209	-1.397	.8317	-1.378	.9017	-0.616	.6587	-0.670
.8604	-1.318	.6256	-1.398	.8335	-1.372	.9050	-0.611	.6603	-0.671
.8641	-1.318	.6274	-1.398	.8352	-1.368	.9084	-0.625	.6620	-0.667
.8673	-1.321	.6291	-1.402	.8401	-1.366	.9118	-0.621	.6667	-0.668
.8705	-1.316	.6339	-1.401	.8429	-1.363	48.9154	-0.616	.6684	-0.669
.8750	-1.313	.6356	-1.404	.8447	-1.353	52.7869	-0.680	.6701	-0.669
.8784	-1.311	.6373	-1.403	.8498	-1.371	.7924	-0.679	.6750	-0.665
.8815	-1.310	.6421	-1.403	.8515	-1.356	.7963	-0.680	.6766	-0.669
.8847	-1.314	.6438	-1.401	75.8533	-1.362	.8007	-0.688	.6783	-0.667
.8889	-1.307	.6454	-1.399			.8050	-0.676	.6830	-0.664
.8921	-1.313	.6501	-1.404			.8097	-0.679	.6851	-0.663
.8951	-1.311	.6518	-1.403	filter B		.8146	-0.683	.6869	-0.665
.8982	-1.311	.6535	-1.405			.8195	-0.679	.6997	-0.666
.9015	-1.302	.6583	-1.396			.8242	-0.682	.7014	-0.667
.9048	-1.316	.6601	-1.400	38.8376	-2.092	.8300	-0.685	.7031	-0.661
.9081	-1.302	.6617	-1.400	.8405	-2.092	.8366	-0.687	.7083	-0.665
.9115	-1.296	.6664	-1.403	.8436	-2.099	.8406	-0.683	.7099	-0.664
48.9152	-1.302	.6681	-1.399	.8490	-2.099	.8455	-0.680	.7116	-0.663
52.7868	-1.388	.6698	-1.400	.8517	-2.097	.8772	-0.682	.7133	-0.661
.7921	-1.387	.6746	-1.399	.8544	-2.094	.8874	-0.688	.7191	-0.662
.7962	-1.391	.6763	-1.398	.8568	-2.096	.8931	-0.692	.7209	-0.662
.8005	-1.393	.6780	-1.402	.8596	-2.094	.9053	-0.682	.7229	-0.659
.8049	-1.388	.6826	-1.396	.8621	-2.094	.9107	-0.688	.7275	-0.657
.8097	-1.384	.6849	-1.396	.8647	-2.098	52.9213	-0.676	.7304	-0.657
.8144	-1.389	.6866	-1.395	.8677	-2.099	54.7945	-0.701	.7321	-0.657
.8192	-1.381	.6993	-1.397	.8713	-2.096	.7988	-0.701	.7373	-0.663
.8241	-1.375	.7011	-1.397	.8738	-2.095	.8030	-0.698	.7391	-0.660
.8298	-1.393	.7028	-1.382	.8765	-2.098	.8075	-0.701	.7409	-0.660
.8364	-1.390	.7079	-1.397	.8794	-2.097	.8116	-0.702	.7461	-0.660
.8409	-1.387	.7095	-1.396	.8823	-2.097	.8156	-0.706	.7478	-0.660
.8454	-1.396	.7113	-1.393	.8851	-2.093	.8198	-0.701	.7495	-0.660
.8771	-1.388	.7130	-1.395	.8882	-2.097	.8239	-0.704	.7548	-0.660
.8873	-1.383	.7188	-1.394	.8911	-2.096	.8291	-0.701	.7565	-0.658
.8929	-1.383	.7206	-1.389	.8939	-2.101	.8338	-0.706	.7582	-0.657
.9051	-1.381	.7225	-1.392	.8968	-2.100	.8407	-0.709	.7634	-0.659
.9106	-1.379	.7272	-1.385	.8999	-2.102	.8456	-0.705	.7650	-0.657
52.9212	-1.390	.7301	-1.391	.9033	-2.098	.8508	-0.713	.7668	-0.656
54.7943	-1.407	.7318	-1.389	38.9063	-2.104	.8557	-0.709	.7720	-0.662
.7986	-1.402	.7370	-1.391	48.7882	-0.614	.8602	-0.713	.7737	-0.660
.8029	-1.407	.7388	-1.389	.7915	-0.610	54.8650	-0.706	.7754	-0.658
.8074	-1.409	.7405	-1.387	.7974	-0.615	75.5765	-0.676	.7804	-0.660
.8114	-1.412	.7457	-1.390	.8003	-0.613	.5781	-0.676	.7822	-0.656
.8156	-1.411	.7475	-1.387	.8033	-0.613	.5798	-0.677	.7869	-0.653
.8196	-1.410	.7492	-1.386	.8066	-0.614	.5847	-0.677	.7897	-0.655
.8237	-1.411	.7545	-1.387	.8089	-0.617	.5864	-0.680	.7925	-0.656
.8289	-1.410	.7562	-1.386	.8128	-0.616	.5881	-0.676	.7990	-0.657
.8336	-1.408	.7579	-1.386	.8160	-0.612	.5934	-0.680	.8007	-0.655
.8406	-1.410	.7630	-1.387	.8206	-0.614	.5949	-0.678	.8024	-0.654
.8454	-1.398	.7648	-1.386	.8239	-0.615	.5966	-0.681	.8073	-0.655
.8506	-1.416	.7665	-1.385	.8269	-0.614	.6015	-0.675	.8090	-0.654
54.8555	-1.411	75.7717	-1.390	48.8301	-0.614	75.6031	-0.676	75.8107	-0.653

Table 1 — concluded.

JD Hel. 2443600+	Δm	JD Hel. 2443600+	Δm	JD Hel. 2443600+	Δm	JD Hel. 2443600+	Δm	JD Hel. 2443600+	Δm
filter B		filter V		filter 4653		filter 4686		filter 4686	
75.8156	-0.656	75.7017	-0.870	52.8148	-0.804	52.8150	-0.767	75.6691	-0.756
.8173	-0.654	.7034	-0.867	.8197	-0.805	.8199	-0.765	.6708	-0.755
.8190	-0.652	.7085	-0.875	.8245	-0.789	.8248	-0.767	.6756	-0.759
.8240	-0.653	.7102	-0.873	.8303	-0.795	.8305	-0.776	.6773	-0.755
.8257	-0.652	.7119	-0.872	.8368	-0.801	.8370	-0.763	.6790	-0.763
.8274	-0.651	.7137	-0.872	.8412	-0.810	.8414	-0.760	.6836	-0.751
.8320	-0.647	.7194	-0.876	.8456	-0.808	.8459	-0.760	.6857	-0.747
.8338	-0.649	.7212	-0.877	.8775	-0.811	.8777	-0.777	.6875	-0.747
.8355	-0.648	.7231	-0.877	.8876	-0.807	.8878	-0.765	.7004	-0.749
.8404	-0.653	.7278	-0.875	.8932	-0.810	.8934	-0.771	.7020	-0.742
.8433	-0.657	.7308	-0.875	.9055	-0.818	.9057	-0.762	.7037	-0.739
.8450	-0.647	.7324	-0.873	.9110	-0.806	.9112	-0.772	.7088	-0.751
.8501	-0.657	.7377	-0.874	52.9215	-0.806	52.9217	-0.775	.7105	-0.752
.8518	-0.656	.7395	-0.874	54.7945	-0.813	54.7949	-0.793	.7123	-0.755
75.8535	-0.643	.7411	-0.872	.7990	-0.824	.7992	-0.787	.7139	-0.755
		.7464	-0.874	.8032	-0.833	.8034	-0.776	.7198	-0.755
		.7481	-0.874	.8077	-0.827	.8079	-0.784	.7216	-0.746
filter V		.7498	-0.871	.8118	-0.824	.8119	-0.778	.7235	-0.744
		.7551	-0.870	.8159	-0.822	.8160	-0.784	.7282	-0.739
		.7568	-0.867	.8199	-0.832	.8201	-0.786	.7311	-0.749
75.5768	-0.892	.7585	-0.868	.8241	-0.828	.8244	-0.785	.7328	-0.746
.5785	-0.891	.7637	-0.868	.8294	-0.826	.8295	-0.786	.7380	-0.752
.5800	-0.892	.7654	-0.868	.8339	-0.826	.8342	-0.776	.7398	-0.749
.5850	-0.892	.7671	-0.867	.8410	-0.826	.8412	-0.779	.7414	-0.750
.5867	-0.890	.7723	-0.868	.8458	-0.823	.8460	-0.779	.7468	-0.757
.5884	-0.895	.7740	-0.869	.8510	-0.830	.8512	-0.791	.7484	-0.752
.5936	-0.890	.7757	-0.869	.8560	-0.831	.8562	-0.790	.7501	-0.749
.5952	-0.885	.7807	-0.871	.8605	-0.847	.8607	-0.791	.7554	-0.747
.5969	-0.884	.7824	-0.863	54.8652	-0.839	54.8654	-0.782	.7571	-0.740
.6018	-0.883	.7873	-0.872			75.5772	-0.765	.7588	-0.746
.6034	-0.888	.7900	-0.872	filter 4686		.5788	-0.769	.7640	-0.743
.6050	-0.887	.7927	-0.870			.5803	-0.764	.7657	-0.745
.6099	-0.895	.7993	-0.872			.5853	-0.768	.7674	-0.749
.6115	-0.888	.8010	-0.871	38.8379	-2.213	.5871	-0.762	.7727	-0.750
.6132	-0.885	.8027	-0.873	.8408	-2.222	.5887	-0.763	.7743	-0.754
.6181	-0.888	.8076	-0.871	.8439	-2.220	.5939	-0.769	.7761	-0.749
.6198	-0.886	.8093	-0.871	.8493	-2.215	.5956	-0.761	.7810	-0.748
.6216	-0.889	.8110	-0.868	.8519	-2.198	.5972	-0.764	.7828	-0.749
.6263	-0.889	.8159	-0.874	.8545	-2.213	.6021	-0.757	.7876	-0.747
.6280	-0.878	.8176	-0.873	.8569	-2.214	.6036	-0.759	.7903	-0.741
.6297	-0.883	.8193	-0.872	.8598	-2.217	.6053	-0.749	.7931	-0.742
.6345	-0.883	.8243	-0.868	.8624	-2.222	.6102	-0.749	.7996	-0.745
.6362	-0.881	.8261	-0.866	.8650	-2.224	.6118	-0.751	.8013	-0.748
.6379	-0.881	.8277	-0.865	.8681	-2.217	.6135	-0.753	.8031	-0.741
.6428	-0.885	.8324	-0.865	.8717	-2.218	.6184	-0.756	.8079	-0.740
.6444	-0.884	.8341	-0.864	.8741	-2.220	.6201	-0.752	.8096	-0.733
.6460	-0.882	.8358	-0.865	.8767	-2.222	.6218	-0.751	.8114	-0.743
.6508	-0.886	.8407	-0.868	.8797	-2.215	.6266	-0.759	.8162	-0.743
.6525	-0.882	.8436	-0.867	.8824	-2.222	.6283	-0.764	.8180	-0.746
.6542	-0.882	.8453	-0.871	.8854	-2.217	.6301	-0.760	.8197	-0.735
.6590	-0.880	.8504	-0.867	.8885	-2.220	.6348	-0.753	.8247	-0.730
.6606	-0.879	.8522	-0.869	.8913	-2.219	.6366	-0.769	.8264	-0.738
.6623	-0.878	75.8539	-0.866	.8941	-2.213	.6382	-0.759	.8281	-0.732
.6670	-0.884			.8971	-2.219	.6431	-0.754	.8328	-0.730
.6687	-0.883			.9002	-2.219	.6448	-0.760	.8344	-0.729
.6704	-0.886	filter 4653		.9036	-2.221	.6463	-0.760	.8361	-0.733
.6752	-0.887			38.9065	-2.224	.6511	-0.754	.8411	-0.733
.6769	-0.880	52.7871	-0.800	52.7873	-0.764	.6528	-0.763	.8440	-0.733
.6786	-0.881	.7924	-0.806	.7927	-0.770	.6546	-0.760	.8457	-0.725
.6833	-0.879	.7965	-0.794	.7967	-0.764	.6593	-0.752	.8508	-0.743
.6854	-0.879	.8009	-0.797	.8012	-0.768	.6610	-0.753	.8525	-0.730
.6871	-0.874	.8052	-0.802	.8054	-0.777	.6627	-0.753	75.8542	-0.730
75.7000	-0.876	52.8100	-0.810	52.8102	-0.768	75.6673	-0.750		

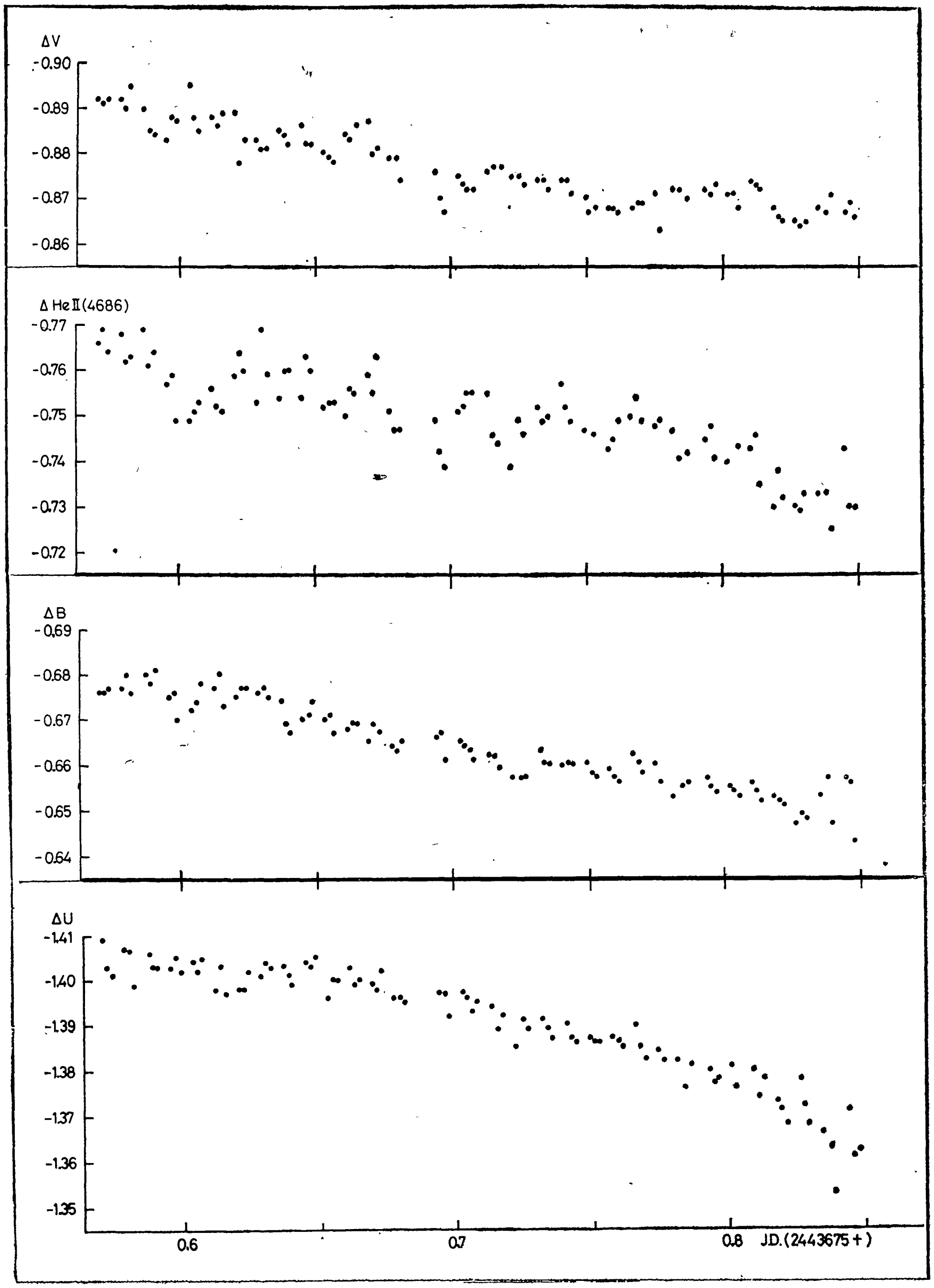

Fig. 1. Photometric observations of HD 153919 obtained at La Silla on June 15, 1978. The comparison star was HD 153767.

The observations were made in May and June 1978 at La Silla with the aid of the 60 cm Bochum telescope equipped with a one-channel photometer. An exception are the observations on JD 2443648 for which the 50 cm ESO telescope was used. The star was measured in the *UBV* filters and also through two interference filters centered on λ4653 Å and λ4686 Å which were 41 Å and 41.5 Å wide respectively.

Table 1 presents these observations. In that table the instrumental magnitude differences Δm between the variable and comparison stars are listed against the time (J. D.). The star HD 153767 was normally taken as the comparison except on J. D. 2443638 when the star HD 153947 was used.

The observations made during May 1978 (observer I. S.) are all outside the optimal orbital phases and they are not well suited for searching the presence of optical pulsations. In addition the *V* filter was not used during May.

The single night June 15, 1978 (observer — J. S.) was in turn very well suited for such a search. The orbital phase ranged from 0.40 to 0.48, equivalent to a run of 7 consecutive hours. Preliminary results of these observations have already been reported (Surdej 1978).

Fig. 1 presents the June 15 observations. The 95 min periodic variations, with the amplitude increasing in course of the observing run and attaining a value about 0.01 mag, are clearly seen from the observations made in the *V* filter. The apparent plusations can be traced since J. D. 2443675.65, corresponding to the orbital phase 0.419. The observations made with the λ4686 Å filter also show variations but the light curve is different. There are two maxima and two minima during a single pulsation cycle. The scatter from these observations is larger and therefore not all maxima and minima are equally well pronounced. The synchronism with the variations observed in the *V* filter holds only since J. D. 2443675.65. Prior to that moment the variations are rather chaotic.

The observations obtained with the *B* and *U* filters do not show directly visible pulsations.

3. Period Determination

Among published photometric observations of HD 153919 there are two additional sets of measurements which could be used in order to search for the cyclic light variations. Both these sets have been obtained with the help of the 91 cm light collector in Hartebeespoordam, South Africa. The first comes from June-July 1975 (van Genderen and Uiterwaal 1976—GU), the second from August-September 1976 (van Paradijs,

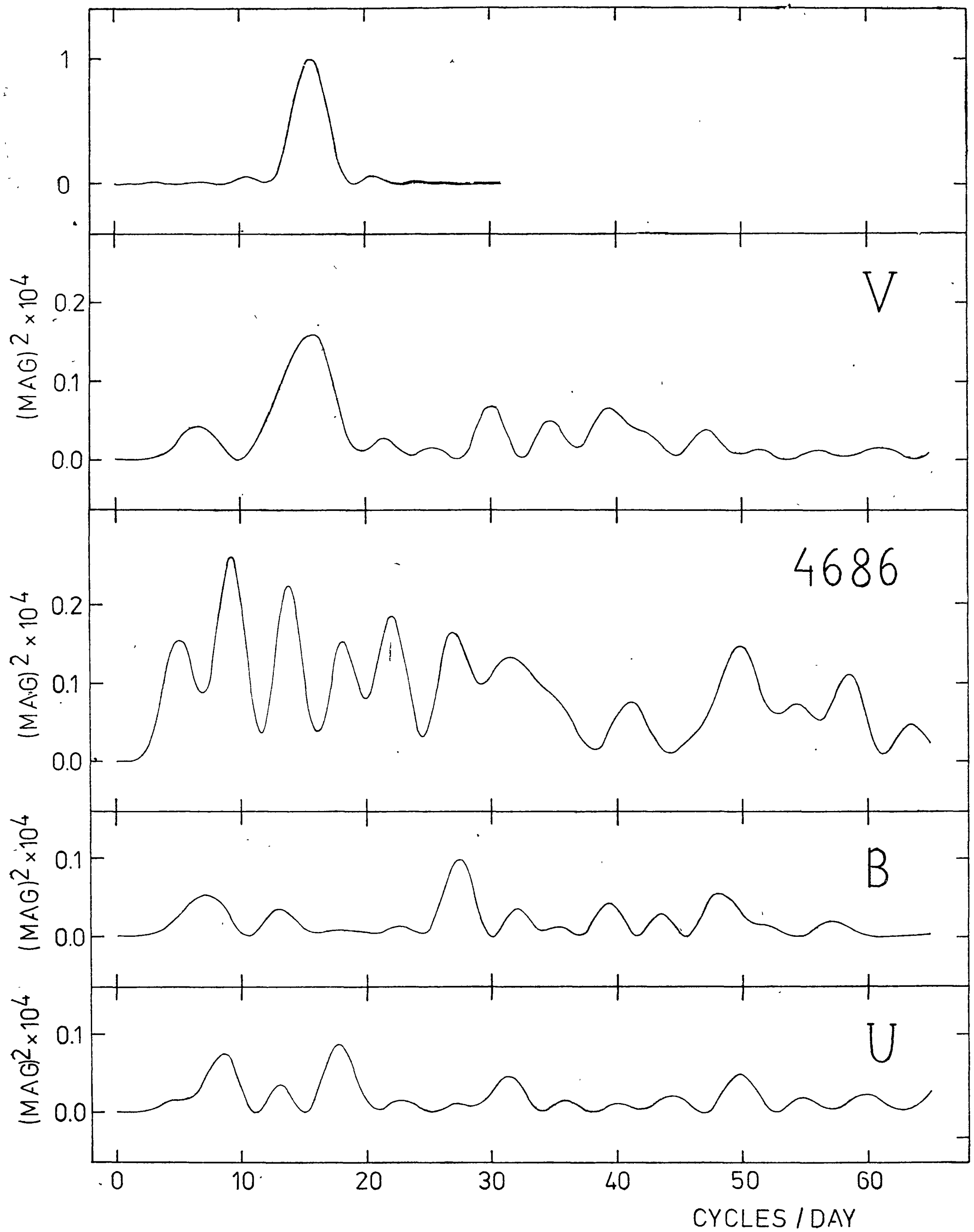

Fig. 2. Power spectra obtained from observations made on June 15, 1978. The ordinate gives the square of the full amplitude expressed in (mag)^2. The window function is given for comparison in the upper diagram.

Hammerschlag-Hensberge and Zuiderwijk 1978 — PHZ). In both cases the Walraven's five colour photometric system (Walraven and Walraven 1960) was used, but GU have only published in a graphical form their observations for the V band. Only the V observations from these two sets of data, supplemented by the ones made on June 15, 1978 at La Silla were considered in order to derive a value for the period of the cyclic light variations.

The first step in this procedure consisted in evaluating the power spectrum. For this purpose we used the algorythm described by Deeming (1975), which is very suitable for unequally spaced data. The observations were detrended by using deviations from nightly means for PHZ data, and deviations from a fitted parabola for each night in the case of GU and La Silla observations. Only the nights with observations covering at least 75 min were used. The night J. D. 2443034 from PHZ data shows a scatter in the observations which is larger by nearly an order of magnitude when compared to the remaining nights. Therefore the night 2443034 was rejected for calculations of the power spectrum.

Fig. 2 shows the power spectra calculated from La Silla observations made on June 15, 1978. All observations made in the four spectral bands were used. The window function which is the same for all filters is given for comparison in the uppermost diagram. The width of the main peak of the window function is inversely proportional to the time interval covering the analysed set of observations. Let us notice that the side-lobes die out quickly due to the fact that the data are nearly distributed uniformly in time. As we could expect from the first graph of Fig. 1, only the V observations lead to a well defined periodicity. The peak in the V power spectrum occurs at $P^{-1} = 15.6$ cycles/day or $P = 92$ min, while the second highest peak corresponds to the second harmonic of the fundamental period. The remaining three power spectra are dominated by noise.

Fig. 3 presents the power spectra from the Hartebeespoortdam observations together with their corresponding window functions. Both power spectra show a number of narrow peaks enveloped by a broad curve. Such a broad envelope corresponds to a peak obtained from a typical single night. We see that the envelope is broader for the PHZ data (see lower diagram) due to generally shorter nightly runs.

The narrows peaks result from making observations during short time intervals, spaced by much longer ones. The separation between two narrow peaks is set by the shortest time span between the nightly runs. The width of the narrow peaks is determined by the total length of a particular set of observations.

In case of the GU data, consisting of only three nights, the closest separation is 7 days, and this results in the separation of two narrow peaks

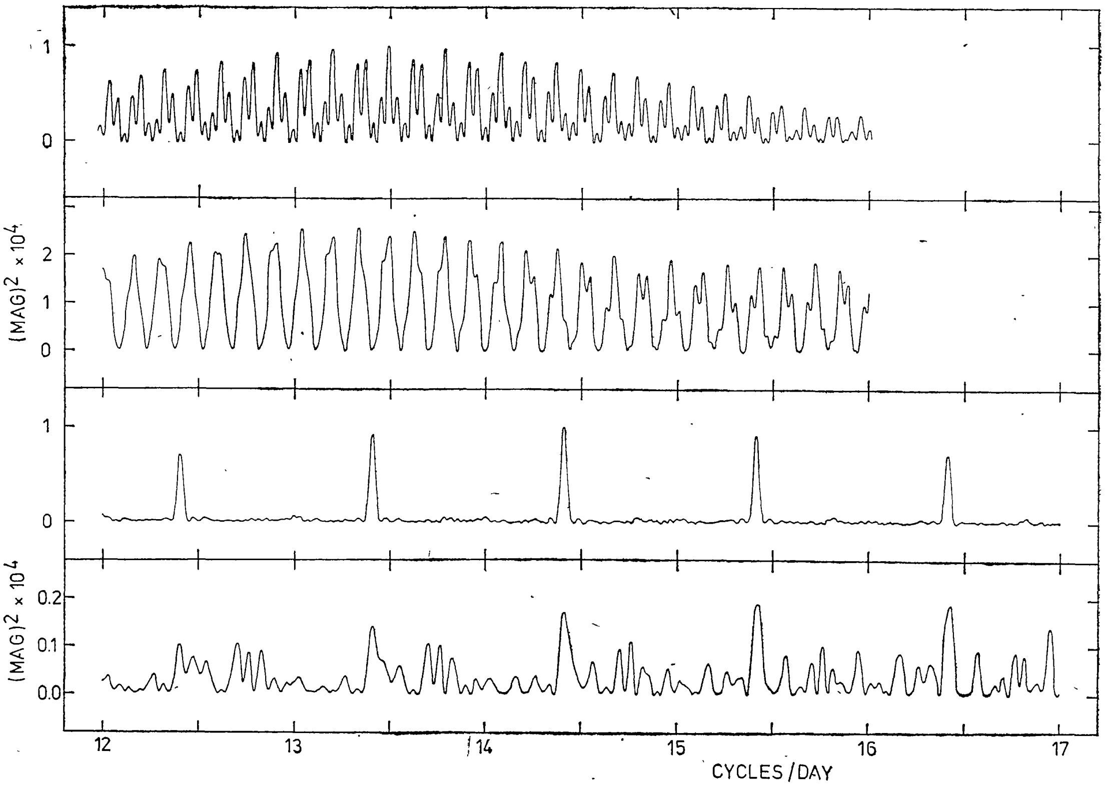

Fig. 3. Same as Fig. 2 but for van Genderen and Uiterwaal observations (upper diagrams) and for van Paradijs *et al.* (lower diagrams) observations.

by only 0.145 cycles/day. The power spectrum is in many respects similar to the window function thus indicating that the data contain a single-periodic component. However, there are some differences. The narrow peaks in the power spectrum appear wider and smoother than expected. This can be understood if one notices that the periodic variations with an appreciable amplitude are only seen in the two first nights — separated by 7 days — out of the three GU nights. Therefore the presence of the third night affects the window function, and has only a very little influence on the power spectrum. Because the narrow peaks are so closely spaced it is impossible to determine a preferred value for the period. We can consider as candidates at least 14 different values centered on $P^{-1} = 13.50$ cycles/day or $P = 106.7$ min.

A different picture emerges from the power spectrum of the PHZ data. The values of the power spectrum are about an order of magnitude smaller than in the case of the GU data. Therefore the contribution due to the noise is felt more strongly than previously. But again the characteristic shape of the window function can be easily identified in the highest peaks of the power spectrum, thus also indicating the presence of one periodic component. There are three peaks in the power spectrum which can be considered as candidates for the period of pulsations $P^{-1} = 14.41$, 15.42, and 16.43 cycles/day.

A natural question is whether there is a single period which can fit all these photometric data. There is only one value $P^{-1} = 15.52$ cycles/ /day coinciding with the narrow peaks in both sets of data and corresponding to the broad peak of the "La Silla" power spectrum. This value is rather too distant from the maximum of the broad envelope in the GU power spectrum, and therefore we tentatively conclude that there is no common period which fits all sets of data.

The power spectra calculated for the three independent sets of optical observations attain their highest values for $P^{-1} = 13.33$, 15.42, and 15.60 cycles/day. These values seem to be significantly close to the X-ray value $P^{-1} = 14.88$ cycles/day (Matilsky *et al.* 1978). Such an approximate coincidence cannot be considered as a proof for the existence of regular pulsations in 4U1700-37. However, it seems to indicate that in this object there is some cyclic variability pronounced both in the X-ray and the optical spectral regions with a characteristic time scale around 100 min.

As the observed optical variability does not seem to be fully regular, it looks worth while to see what we can infer about the periodicity of variations from observations obtained on each individual night. The following procedure was used in order to look for periodic variations during a single night. For a trial value of the period P the observations were fitted by the least squares method to the expression consisting of the four first harmonics in the Fourier expansion supplemented by the equation of parabola. In this way we obtain a sum of squares of deviations from the solution as a function of the trial period

$$Q(P) = \sum_{i=1}^{n}\left[m_i - A - Bt_i - Ct_i^2 - \sum_{k=1}^{4}\left(a_k \cos\frac{2\pi k}{P}t_i + b_k \sin\frac{2\pi k}{P}t_i\right)\right]^2,$$

where n is the number of observations, and m_i the observed magnitude at time t_i. Having the function $Q(P)$ we can determine the estimated $\hat{P}$ from the condition that $Q(\hat{P})$ is minimum, furthermore, with the help of the ratio-of-variances criterium we can determine confidence intervals for P (Lampton *et al.* 1976, Cash 1976). Not every night has sufficiently good data in order to get a meaningful solution. Therefore, only the best nights have been used. They include the V and HeII 4686 data from La Silla night on June 15, 1978, all three nights from the GU observations, and only those nights from the PHZ data which satisfy the following criteria: the length of the observing run is longer than 200 min and the system falls outside the total X-ray eclipse. The odd night 2443034 was of course rejected.

Table 2 summarizes the results. The presented mean errors are correct under the assumption that the deviations from the calculated curve are solely due to the observational errors. If these deviations are also due to irregular changes of brightness or nonrepeatability of the pulsation curve, then we expect that the true mean errors are larger than the estimated ones. Therefore, to be on a safe side, the estimated errors should be regarded as lower limits.

The accuracy of the observations is determined by the mean error σ_0 of a single measurements expressed in magnitudes. The quantities determined from the solution are accompanied in Table 2 by their mean errors denoted by m.e. The resulting periods show a tendency to cluster around a specific value for a given set of data. There are two or three grossly deviating values. One of the deviating values is from the He II 4686 La Silla observations. In this case the deviating value of the period is evidently due to the erratic behaviour of brightness during the first two hours of the observing run. Therefore a separate solution has been obtained when considering only the observations recorded after J. D. 2443675.65. This solution is denoted by an asterisk in Table 2.

Table 2

Periods, amplitudes and times of maximum of short term optical variations for individual nights.

J.D.2440000+	filter	σ_0	cycles/day	±m.e.	First harmonic full amplitude in magnitudes	±m.e.	Second harmonic full amplitude in magnitudes	±m.e.	Time of maximum in J.D.	±m.e.
2574.	V	$0^{\mathrm{m}}.007$	13.45	0.38	0.023	0.009	0.016	0.009	0.452	0.005
2581.	V	.016	13.93	.62	.024	.007	.025	.008	.354	.003
2598.	V	.014	14.81	.63	.002	.009	.021	.008		
3011.	V	.007	13.53	.37	.008	.004	.008	.004	.361	.005
3013.	V	.010	17.15	.79	.004	.004	.003	.004	.308	.014
3016.	V	.010	14.05	.20	.006	.004	.003	.004	.302	.007
3017.	V	.013	14.10	.59	.031	.010	.008	.010	.334	.004
3024.	V	.005	14.32	.63	.018	.007	.014	.007	.271	.004
3030.	V	.006	14.05	.38	.004	.003	.006	.003	.257	.011
3031.	V	.010	13.81	.68	.011	.004	.004	.004	.277	.005
3675.	V	.003	15.33	.17	.0040	.0008	.0008	.0008	.769	.002
3675.	4686	.005	13.62	.21	.0048	.0015	.0039	.0015	.761	.004
3675.	4686*	$0^{\mathrm{m}}.005$	14.80	0.35	0.0034	0.0017	0.0066	0.0016	0.764	0.005

*Without first two hours of observations

Weighted averages for each set of data are $P^{-1} = 13.83 \pm 0.29$ (m.e.) cycles/day for GU observations, 14.08 ± 0.15 (m.e.) cycles/day for PHZ observations and 15.22 ± 0.15 (m.e.) cycles/day for the La Silla observations. These values are in reasonable agreement with the power spectra. The greatest deviation is observed in the PHZ observations. The value of inverse period derived from the above period determination is smaller by 0.33 cycles/day (or about twice its mean error) than the smallest possible value inferred from the power spectrum. It effectively restricts our choice of the inverse period to the value 14.41 cycles/day which corresponds to $P = 99.9$ min. In the case of the GU data there is still ten or more possible values of the period.

4. Wavelength Dependence of the Amplitude

Looking at Figs. 1 and 2 we can see that the amplitude of the short term variations is wavelength dependent. It is therefore interesting to investigate this dependence quantitatively.

Fig. 4 presents the pulsational light curves for the La Silla measurements made in the four spectral regions on June 15, 1978. The averages

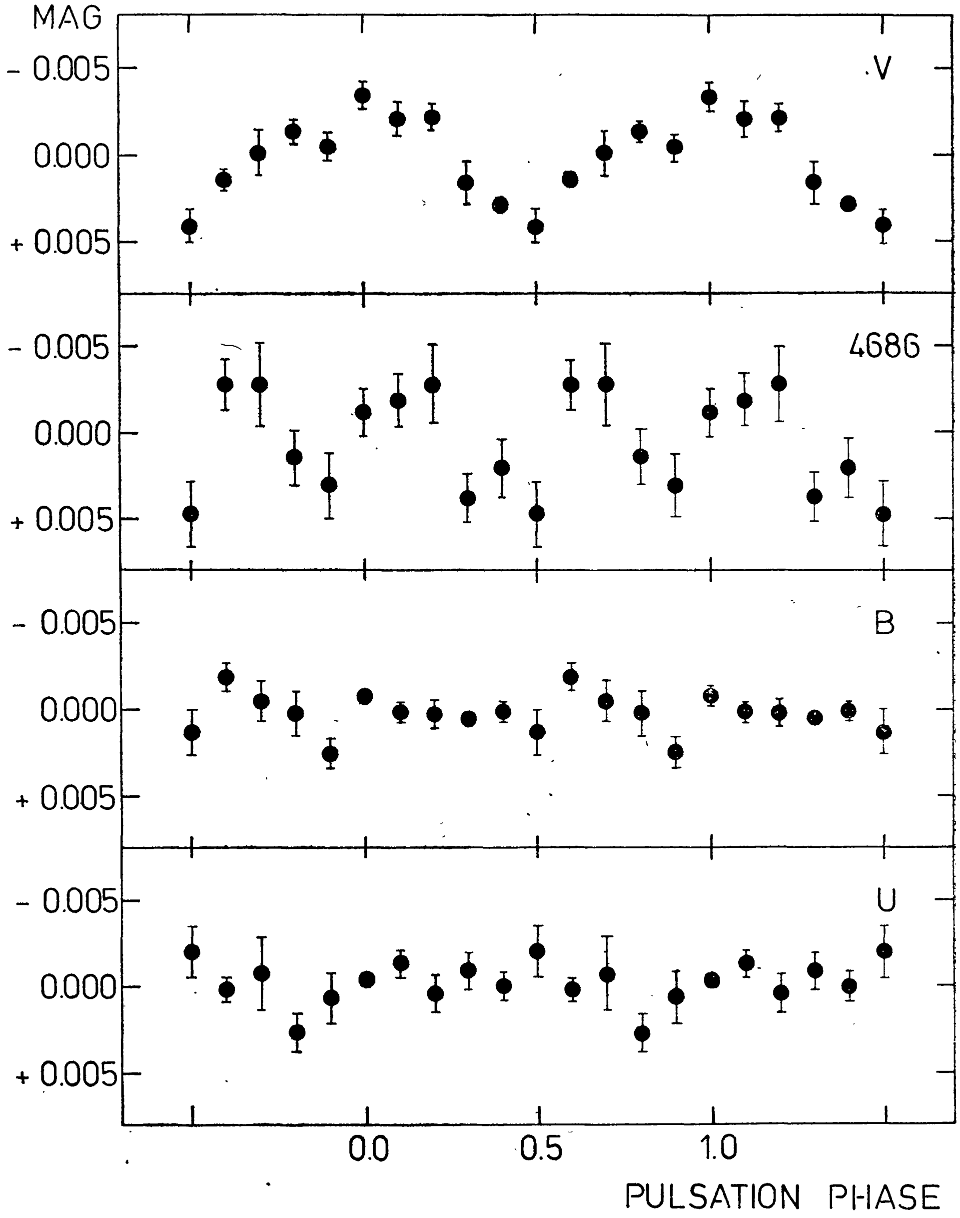

Fig. 4. The pulsational light curve for La Silla observations (June 15, 1978) constructed by folding the detrended observations with the period of 94.6 min. Only the observations obtained after J. D. 2443675.65 were used.

pictured in Fig. 4 were obtained by folding the detrended observations with the period of 94.6 min. Only the observations obtained after J. D. 2443675.65 were used. We can see that the first harmonic is clearly seen only for the *V* observations. The second harmonic is in turn dominating in the observations of the helium emission line 4686.

There is another multicolour set of observations (PHZ). However, these observations only show a weak dependence of the pulsational light curve on the wavelength.

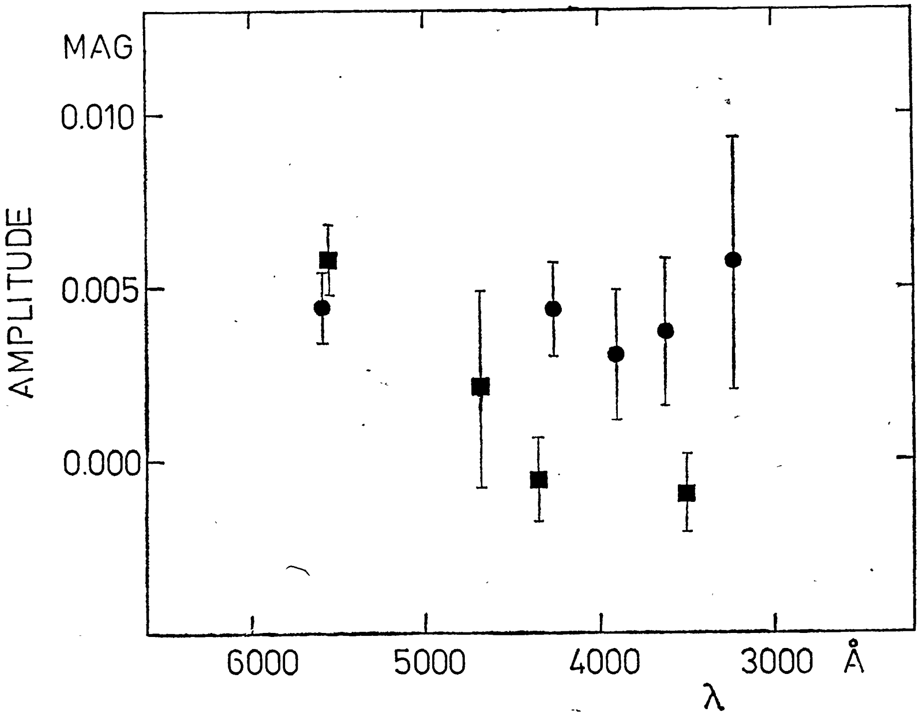

Fig. 5. The wavelength dependence of the full amplitude of cyclic variations. A negative value means that the maxima are interchanged with the minima. Filled circles denote van Paradijs *et al.* (1978) data. Filled squares correspond to the June 15 La Silla observations.

Fig. 5 gives a comparison of these two wavelength dependences of the amplitude. Only the amplitudes of the first harmonic are illustrated. A negative value means that the maxima are interchanged with the minima. The evident differences might not be so surprising if one remembers that one set of data was obtained on a single night in a narrow range of the orbital phases, while the second set of observations covers one month or nine orbital cycles.

5. Time Dependence of Amplitude

It has been noticed that the amplitude of light variations was dependent on the binary orbital phase (Kruszewski 1978). We shall now investigate this effect and in addition we shall look at the behaviour of the amplitude on longer time intervals.

The observational material published by van Paradijs, Hammerschlag-Hensberge, and Zuiderwijk (PHZ) is well suited for such an investigation. It includes 21 nights within an interval of 30 days, the observations lasting 75 min or longer. We have seen in Sec. 3 that only for a few best cases the amplitude of variations could be determined from the observations made on a single night. In general it is not possible. Therefore the nights have been divided into 5 groups, each consisting of between two and seven nights depending on the orbital phase. For each of these groups the full amplitude and the phase of the first Fourier harmonic, with the period fixed at $P = 99.9$ min ($P^{-1} = 14.41$ cycles/day) were determined. Data from any particular night were assigned to only one group and therefore the pulsational light curves obtained for each group are mutually independent.

Fig. 6 shows the dependence of the amplitudes and phases of the short period variations on the orbital phase, together with the orbital phase dependences of other pertinent quantities. In particular the schematic X-ray and optical light curves are shown for comparison. In addition the data on circular polarization are also presented. The filled circles correspond to root-mean-square values obtained by Kemp and Wolstencroft (1973) from their H_β observations. The open circles denote the absolute values of a single measurement of Angel *et al.* (1973) in the region of H_α. One should note that symbols falling outside the region of the orbital phases between 0.4-0.8 are consistent with measurement errors which are 0.02 % for the open circles and 0.05 % for the filled ones.

We can see a striking similarity between the dependences on the orbital phase of the amplitudes of variations in brightness and in circular polarization. This similarity indicates that the short term variations of circular polarization observed by Kemp and Wolstencroft may be related to the optical pulsations.

The maximum amplitude of photometric variability occurs around the phase 0.5 *i.e.* when the X-ray source is in front of the optical component. The region of high amplitude extends also after the conjunction up to the phase 0.7. It should be noted that the corresponding optical minimum, which is deeper than the optical minimum coinciding with the X-ray eclipse, is also shifted after the time of conjunction (Hutchings 1974, PHZ). There are many spectroscopic evidences indicating that during the phases

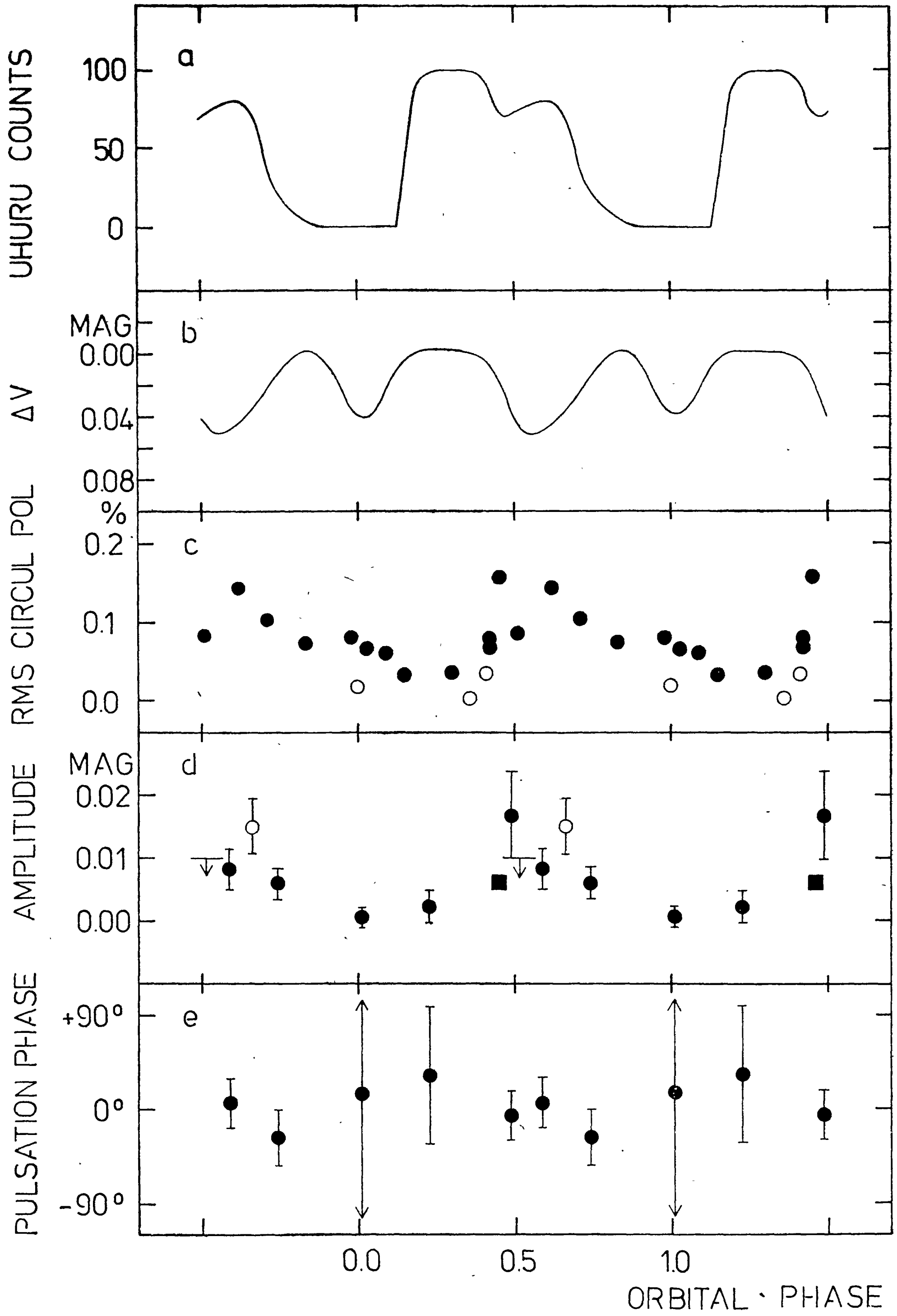

Fig. 6. Various data plotted as a function of the orbital phase. (*a*) A schematic X-ray curve based on the observations of Jones *et al.* (1973), Mason *et al.* (1976), and Branduardi *et al.* (1978). (*b*) A schematic optical curve based on the V observations of van Paradijs *et al.* (1978). (*c*) Root mean square circular polarization after measurements of Kemp and Wolstencroft (1973) — filled circles — and Angel *et al.* (1973) — open

0.50-0.77 the light from the optical component goes through a relatively dense cloud of gas usually referred to as "an accretion wake" (Walker 1974, Conti and Cowley 1975).

The amplitudes and phases of the short period variability have been calculated as follows. At first the phase of each individual observation was calculated with the help of the ephemeris J. D. (maximum) $= 2443024.267 + 0.069377\,E$, which gives expected times of maxima in the case of the PHZ data. Next, for each of five groups of nights clustered around specific orbital phase, the detrended observations were sorted in the bins of the pulsational phase. The average magnitudes were then calculated for all bins and the results were fitted into a cosine-curve. This gives the amplitudes of variations and deviations from the average phase for each group of nights. The resulting amplitudes and deviations of phases are plotted in two lowest diagrams of Fig. 6. The amplitudes have been also calculated for other sets of data.

The deviations of the times of maxima are expressed in degrees so that 360° stands for a full pulsational cycle. The mutually independent meaningful values of the phase deviation range between $-26°$ and $+33°$ thus supporting the existence of coherent optical pulsations in this set of data.

There is some trend in the phase angles, statistically not significant, in the PHZ data, but nevertheless one should be aware of such possible effect. There are many reasons to expect that the optical variations are induced by a variable X-ray flux. Therefore the phase of the optical variations may be shifted with respect to the X-ray variations, and this shift may depend on the orbital phase.

Fig. 7 gives the temporal behaviour of the optical pulsations derived from the PHZ data. Each point is a running average from 5 consecutive nights. In each set of 5 nights there are at least 3 nights which include effective observations. The taking five consecutive nights is just enough to cover a little more than a single orbital cycle. Therefore the dependence of the amplitude on the orbital cycle should not have any appreciable

circles. Errors due to photon statistics which are about 0.05 % in the Kemp and Woltenscroft data and 0.02 % in the Angel *et al.* data explain the positive values outside the interval 0.4-0.8 of the orbital phases in both sets of data. (*d*) The full amplitudes of pulsations expressed in magnitudes. Filled circles correspond to van Paradijs *et al.* data. The filled square denotes the La Silla June 15, 1978 point. The upper limit is that of van Genderen (Hammerschlag-Hensberge *et al.*, 1979). The open circle stands for van Genderen and Uiterwaal data. (*e*) $O-C$ deviations for the maximum of the pulsational light curve from van Paradijs *et al.* (1978) observations calculated with respect to the ephemeris: J. D. $= 2443024.267 + 0.069377E$. The deviations are expressed in degrees so that 360° stands for a full pulsational cycle.

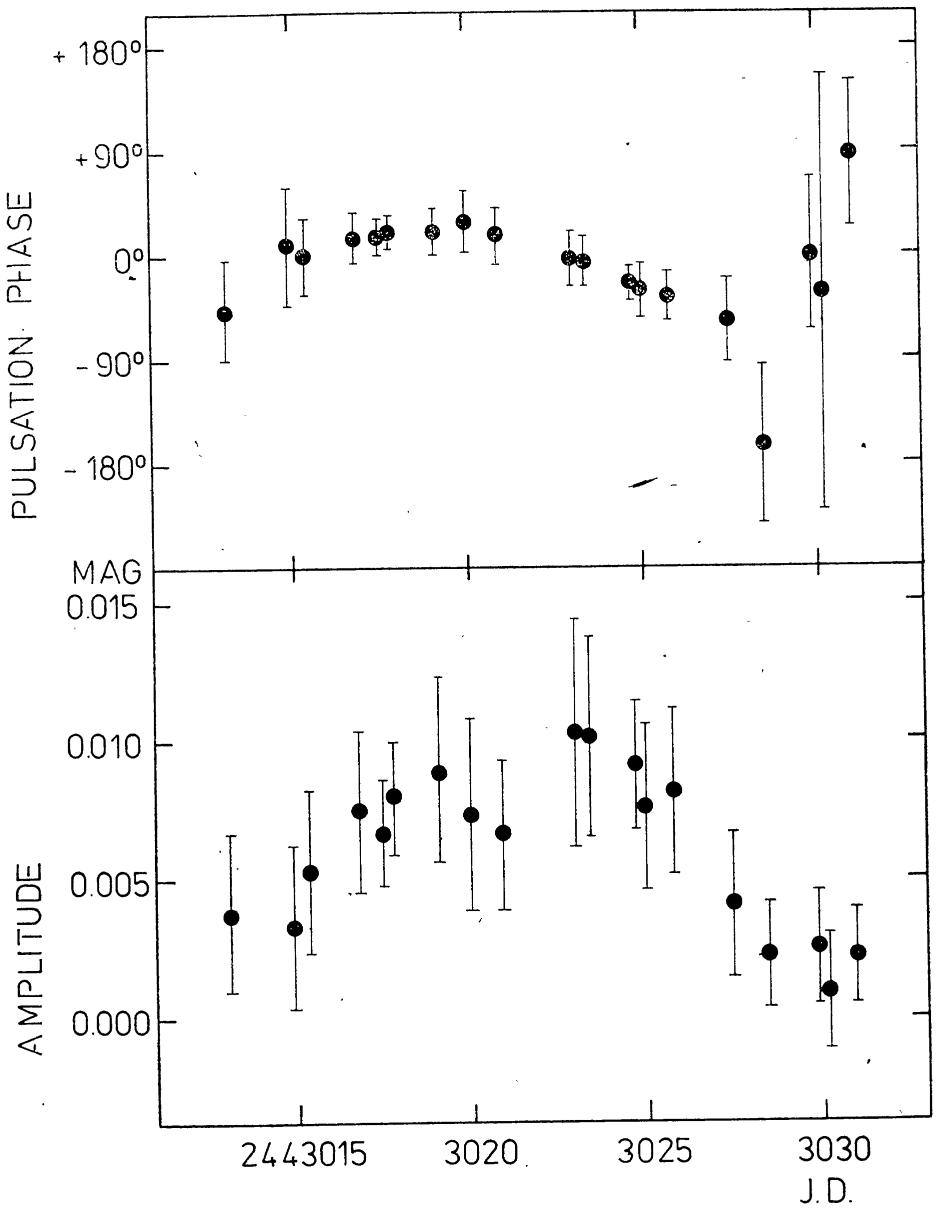

Fig. 7. The time dependence of the full amplitude and phase of maximum of the optical pulsations in the data of van Paradijs *et al.* (1978). Each point is a running average from 5 consecutive nights. The error bars denote mean errors.

influence on the data in Fig. 7. The values of the amplitude and phase deviation have been evaluated in the same way as those plotted in Fig. 6. The only difference is that now the data from any night are used for calculating five consecutive points, while previously they were used only once. Therefore, in Fig. 7 only those points are independent which are separated by at least 4 other points. We can see that the coherent oscillations persisted for nearly two weeks. Later than J. D. 2443025 the amplitude cease to be measurable and the phase coherence was lost. It should be noted that the phase points do not lie on a straight line. The observed curvature in the phase diagram indicates that the period is decreasing. The apparent e-folding time of the observed period shortening is about 5 years, but the data may also be consistent with values as long as 20 or even 30 years.

6. Period Variations

From the currently adopted theory of disk accretion (Mason 1977, Rappaport and Joss 1977) one expects that a period as long as 100 min for the spin of a neutron star component in a close binary system should decrease very rapidly. However, the relatively low X-ray luminosity of 4U1700-37 safeguards this object from the life-time difficulties. Taking the following formula (Rappaport and Joss 1977) for the spin up

$$\dot{P}/P = -3\cdot 10^{-5}\left(\frac{P}{1\,\mathrm{s}}\right)\left(\frac{L}{10^{37}\,\mathrm{erg\,s^{-1}}}\right)^{6/7}\mathrm{yr}^{-1}$$

and accepting 5808 s for the period (Matilsky *et al.* 1978), and 10^{36} erg/s for the luminosity (Jones *et al.* 1973) we obtain $\dot{P}/P = -0.024\,\mathrm{yr}^{-1}$, and the corresponding e-folding time is 42 years. Jones *et al.* give in fact a value of 3×10^{36} erg/s which is based on the highest value of a measured flux. Because of large short term variability this highest value is about four times larger than the average outside the eclipse flux. The above theoretical e-folding time is sufficiently long to be consistent with 8 years of documented existence of 4U1700-37 as an X-ray source.

It is very interesting to look in the available data whether there are any evidences supporting this decrease of the period. We can use the three sets of optical data and the X-ray period reported by Matilsky *et al.* (1978). Among other observational data, there is an additional set of X-ray observations (Mason *et al.* 1976) which is published in a sufficiently detailed form to allow for a tentative period determination. These observations obtained in 1974 apparently show a cyclic behaviour with a possible period of 112.5 min.

Basing on all these data we illustrated in Fig. 8 the temporal behaviour of the period for 4U1700-37. It is strongly suggestive that the period, or to say defensively, the characteristic time scale of variations, is speeding up with an e-folding time around 30 years. The agreement between the theoretical and the observed rates of the speed up can be considered as an argument in favour of the pulsational nature of the X-ray and optical variations. Even using the value $3\cdot 10^{36}$ erg/s for the luminosity would not cause life-time difficulties nor lead to serious conflict with the observed spin up.

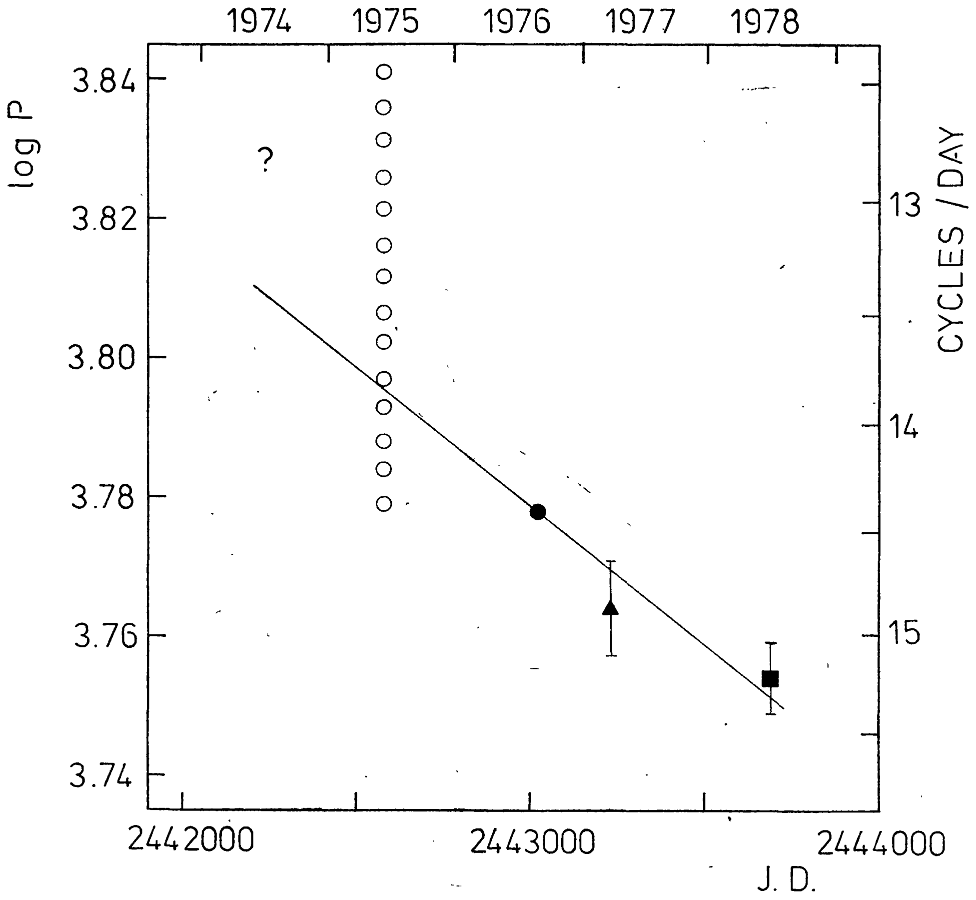

Fig. 8. The available data on the time variability of the period of cyclic variations in 4U1700-37 = HD 153919. Both X-ray and optical data are plotted. The question mark denotes a tentative value of period derived from X-ray observations of Mason *et al.* (1976). The set of open circles illustrates the possible aliases fitting the optical observations of van Genderen and Uiterwaal (1976). The filled circle corresponds to the nearly unique period for the van Paradijs *et al.* (1978) data. The filled triangle stands for the X-ray period derived by Matilsky *et al.* (1978). The filled square denotes the period derived from La Silla optical observations.

7. Conclusions

There is quite a number of evidences in favour of the existence of cyclic optical variability of HD 153919 with a period around 100 min. These variations can be directly seen from the V light curve obtained on June 15, 1978 illustrated in Fig. 1. The power spectra presented in Fig. 3 for the observations of van Genderen and Uiterwaal (1976) and of van Paradijs *et al.* (1978) show sets of aliases, very similar to the window functions, with a peak at frequencies corresponding to periods around 100 min. The direct period determination for the best individual nights give values consistent with the results of the power spectrum analysis. In particular the power spectrum analysis and the direct period determination taken together are sufficient for determining a nearly unique value $P = 99.9$ min from the PHZ data. The amplitude of variations shows a strong dependence on the orbital phase, becoming negligibly small during the total X-ray eclipse. From the PHZ data, a cycle count can be performed during a time interval of two weeks. The observations carried out during these two weeks show a well expressed speed up of the pulsational period. The combining of all available data also leads to the conclusion that there is a secular decrease of the period. The rate of the inferred speed up of the pulsational period agrees very well with the theoretical prediction based on the model of disk accretion onto a neutron star.

Therefore it seems well established that the star HD 153919 shows optical cyclic variations with an amplitude up to 0.02 mag, and with a characteristic period around 100 min. It seems likely that these optical variations are related to the reported (Matilsky *et al.* 1978) X-ray variability. It is tempting to conclude that 4U1700-37 = HD 153919 is an X-ray and optical pulsar. In order to prove this it is necessary to establish that the X-ray and optical variations are coherent during long time intervals. Until now the longest observed interval of optical coherency was two weeks.

The observed variations are not very regular. Besides the changes of the amplitude as a function of the orbital phase, the amplitude changes also on longer time scales, and it is possible that the variations completely disappear at times. It would be very interesting to know whether the phase is preserved at the moment of re-appearance of these variations. However a rapid decrease of the period makes such a check difficult. Therefore it would be very important to analyze simultaneous or nearly simultaneous X-ray and optical observations. Fortunately, two most extensive sets of optical observations were made during periods when the Copernicus satellite was also observing in the X-ray spectral region (Branduardi *et al.* 1978). The GU optical observations ended a few days before the X-ray measurements started, and the PHZ observations started a few days after the 1976 set of X-ray observations was ended. These X-ray observations are not published with a sufficient time resolution to make the period determination possible, however these were telemetered with a time resolution of 63 s or 9.7 s which is amply sufficient in order to make such an analysis.

The comparison of the optical and X-ray periods is important in order to conclude whether the short term variations in they two spectral regions have a common origin. The X-ray period needs not be exactly equal to the optical one. If the optical variations are due to the variable

X-ray radiation reprocessed in the atmosphere of the optical component, then these two periods should differ by 2 min, and the sign of this difference depends on the direction of the pulsar rotation with respect to the direction of the orbital motion (Middleditch and Nelson 1976, Chester 1979a). From a model of the optical pulsations due to the X-ray radiation reprocessed in the atmosphere of the optical component (Chester 1979a) it follows that in HD 153919 one should expect the optical pulsations to occur with the maximum amplitude (around 0.01 mag) at the orbital phase 0.5 (Chester 1979b).

The presence of the very intense stellar wind outflowing from the optical component may suggest another origin for the optical pulsations (Kruszewski 1978). The largest amplitudes of the optical variations are confined to the phases when photometry and spectroscopy indicate that the light of the optical component is attenuated in a cloud of gas situated nearby the X-ray component. The X-ray pulsations modify periodically the physical conditions and the velocity field in the nearby gas, and this in turn influences the transparency of the gas cloud and consequently the fractional light loss and the optical brightness of the system. This mechanism may also require some phase drift of the optical pulsations with respect to the X-ray pulsations, but it is difficult to predict the exact nature of such an effect. It is also possible that both mechanisms work at the same time in 4U1700-37.

Though we still have to wait for a confirmation that the observed optical variations are related to the X-ray pulsations this object appears to be very interesting. It is very bright (6.6 mag) and the amplitude of variations is sufficiently large for it being observed with a small telescope. Photometric observations performed with proper care should allow to detect on a single night pulsations with an amplitude of the order 0.002 — 0.003 mag. In a possible case, that 4U1700-37 is an optical and X-ray pulsar, such observations could be used for studying the period variations of pulsations and therefore they would constitute a cheap source of data, usually obtainable with X-ray satellites only.

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