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The 59 s Periodicity of 2CG 195 + 4 (Geminga) and a Low-Mass Binary Model

D. A. Leahy *Department of Physics, The University of Calgary, Calgary, Alberta, Canada T2N 1N4*

S. V. Damle & S. Naranan *Tata Institute of Fundamental Research, Bombay 400005*

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Abstract. An examination of the existing period searches for 2CG195 + 4 leads to the conclusion that the 59 second periodicity is highly significant only for the 1981 March 17–18 detection of Bignami, Caraveo & Paul (1984). The statistical significance is increased substantially if the pulsation period is half the previously reported value. The period derivative is not well determined. Here we propose that 2CG 195 + 4 is a neutron star powered by accretion from a low ($\lesssim 1M_\odot$) mass main-sequence companion. A distance of a few hundred pc would imply that the neutron star is a fast rotator and is spinning down.

Key words: accretion—gamma-ray sources—pulsation—X-ray sources

1. Introduction

The high energy γ-ray source 2CG 195 + 4 (Geminga) has recently attracted much attention. Bignami, Caraveo & Paul (1984, hereafter referred to as BCP) report an increasing 59 s period based on Einstein and Exosat soft X-ray observations. Zyskin & Mukanov (1983, hereafter referred to as ZM) give evidence for the 59 s period from observations of Cerenkov flashes from 10^{12} eV γ-rays. An optical counterpart (m_v = 21.3) has been reported (Caraveo *et al.* 1984; Sol et al. 1985). However, its association with Geminga has been questioned (Halpern, Grindlay & Tytler 1985) and two fainter (24.5 and 26 mag) candidates have been recently reported (Djorgovski & Kulkarni 1986). In this paper we discuss the 2CG 195 +4 period searches. Then we develop a low-mass binary accretion model consistent with the observations to date.

2. 2CG 195 + 4 period searches

Pulsation at high energy was first reported from SAS 2 data (Thompson *et al.* 1977), then from COS B data (Masnou *et al.* 1977). The latter was subsequently retracted (Masnou *et al.* 1981). Here we consider the recent results of ZM for photon energies greater than 10^{12} eV and of BCP for low energy X-rays (0.2 to 4 keV). The reported detections are summarized in Table 1. The uncertainty in the period was not given by BCP. We quote for the period uncertainty, the spacing between statistically independent periods, $P^2/(2T_s)$, with T_s the timespan of the data set. The highest χ^2 value from the searches, all of which used epoch folding, is given in column 3, and the number of degrees of freedom (number of bins minus 1) in column 4. ZM used 10 degrees of freedom instead of the correct 18 (Buccheri *et al.* 1985 have previously pointed this out). P_1 is the probability using Pearson's χ^2 test, that a single trial will yield by chance (with no signal) a χ^2 value greater than the value in column 3. *N*is the number of trial periods and P_N is the probability that the χ^2 value of column 3 is exceeded by chance in *N* trials.

Applying the run test (Eadie *et al.* 1971) to the folded light curves yields chance probabilities of 0.51 (1981 Feb.6–8), 0.64(1981 March 17–18) and 0.41(1983 Sep. 9), for joint chance probabilities ($= p_1 p_2[1 - \ln(p_1 p_2)]$) of 0.14, 4.1×10^{-3} (4.5×10^{-2}), 0.05 (0.68) respectively, where the values in parantheses are for the 10^4 step searches Thus the confidence levels of March 17–18, 1981 detection is high, 95.5 to 99.6 per cent, whereas the confidence levels of the other four are low.

We note here that no epoch folding has been done at the statistically independent periods around 30 s (half the 60 s period) despite the appearance of a double peak separated by 5 bins in the 10-bin folded curve. A simple folding at 59.737/2 s and 60.056/2 s of the 1981 March 1718 and 1983 September 4 light curves in the 5 bins yields χ^2 values of 35.60 and 30.14; *i.e.* single-trial chance probabilities of 3.5×10^{-7} and 4.6×10^{-6} respectively. The associated increase in confidence level indicates the true period may be near 30 s.

For the light curves of ZM and BCP we find measured amplitudes $(n_{\max} - n_{\min})/(n_{\max} + n_{\min})$ of 0·36 ± 0·09 (1981 February 6–8)and 0.41 ± 0.07 (1981 March 17–18)and 0.38 ± 0.10 (1983 September 9). From the χ^2 values the expected amplitudes for a sine wave (*e.g.* see Equation (15) of Leahy *et al.* 1983) are 0.15, 0.20 and 0.21 respectively. These values are consistently less than the first set because of the large contribution of single bins to χ^2 in all the three observed light curves. One might take this to imply that the light curves cannot be dominated by a single harmonic. However, considering the high chance probabilities for all but the 1981 March detection, the high single bins are likely to be of statistical origin. The uncertainties in the period determination are less than the period changes between measurements. The SAS 2 and COS B periods give $\dot{P}/P \simeq 4 \times 10^{-11}\ \mathrm{s}^{-1}$, whereas the two ZM periods give $\dot{P}/P \simeq -5 \times 10^{-11}\ \mathrm{s}^{-1}$ and the three BCP periods give $\dot{P}/P \simeq 8 \times 10^{-11}\ \mathrm{s}^{-1}$. The 1981 February 6–8 (ZM) and the 1981 March 17-18 (BCP) periods give $\dot{P}/P \simeq 3 \times 10^{-9}\ \mathrm{s}^{-1}$. One may accept at face value, a rapidly changing $\dot{P}/P$, but considering the complication of period Doppler shifts due to binary motion, one can still have a steady intrinsic $\dot{P}/P$. Furthermore, since only the March 1981 period, of all those above, has been detected with high confidence, we cannot rely on the above $\dot{P}/P$ values. So, the unknown intrinsic $\dot{P}/P$ is written as

$$\dot{P}/P = -\beta\,(5 \times 10^{-11})\ \mathrm{s}^{-1} \qquad (1)$$

The alternatives of rapidly changing $\dot{P}$ or binary motion (or both) would rule out an isolated pulsar model for Geminga. This is consistent with the observed lack of radio emission and we will not consider the isolated pulsar alternative further. For a change in the observed periods due to binary motion we assume a circular orbit (radius a) and consider the 1981 February 6–8 and 1981 March 17– 18, periods. The $\Delta v \sim 2300\ \mathrm{km\ s}^{-1} < 2\ v_{\mathrm{orb}}$ gives $a < 1.0 \times 10^{10}\,(M_1 + M_2)$ cm and $P < 540\,(M_1 + M_2)$ s with masses in solar units. However, the observation spans are approximately

Table 1. Statistical significance of detections of 59 s periodicity of 2CG 195 + 4.

Date (ref.)	Period (error)	χ^2	ν	P_1	N	P_N
1979 Jan. 29–Feb. 1 (ZM)	59.46 (.01)	33.6	18[b]	1.4×10^{-2}	200	0.94
1979 Sept. 29 (BCP)	59.466 (.05)	32.4	9	1.7×10^{-4}	400	0.066
1981 Feb. 6–8 (ZM)	59.28 (.01)	43.6	18	6.6×10^{-4}	100	0.064
1981 Mar. 17–18 (BCP)	59.737 (.064)	44.3	9	1.2×10^{-6}	600, 10^4[a]	7.4×10^{-4}, 1.2×10^{-2}[a]
1983 Sept. 9 (BCP)	60.056 (.05)	34.7	9	6.7×10^{-5}	300, 10^4[a]	2.0×10^{-2}, 0.49[a]

[a] Separate values for two searches.
[b] It is assumed $\nu = 18$ as in 1981 Feb. 6–8 (ZM). In the latter, ν is quoted erroneously by ZM as 10, the correct value being 18 (Buccheri *et al.* 1985).

10^5 s, so averaging over an orbit should occur except at long periods. Orbital periods greater than 10^5 s require $M_1 + M_2 > 200\ M_\odot$, at variance with optical observations unless one of the objects is a massive black hole. In this case the low-mass object would be the source of both the X and γ-ray radiation to give the large Doppler shifts.

3. Low-mass accretion binary model

The ratio of X-ray flux (0.2 to 4 keV) to γ-ray flux (> 100 MeV), L_X / L_γ is 10^{-3}. This suggests that X-rays may be due to reprocessing of γ-rays on the surface of a companion to the γ-ray source (as suggested by BCP).Then using the best period data and ignoring $\dot{P}$ over the one month interval in 1981, we find a binary period (= beat period) of 7700 ± 1200 s. Kepler's law gives

$$a = (M_1 + M_2)^{1/3} (5.9 \pm 0.6) \times 10^{10} \text{ cm} \tag{2}$$

and for a circular orbit, the velocity of M_1

$$V_1 = 490 (M_1 + M_2)^{-2/3} M_2 \text{ km s}^{-1}. \tag{3}$$

Fig. 3b of BCP allows an upper limit to be placed on V_1 of 370 km s^{-1}. This is obtained by noting that the peak in χ^2 versus period has a width of 0.15 s which is similar to the predicted value P^2/T_s with T_s the timespan of the observation. For a γ-ray source mass (M_2) of 1.4 $M_\odot$ (*i.e.* a neutron star), we find $M_1 > 1.1\ M_\odot$ and a > 8 × 10^{10} cm. For M_2 as low as 1.0 $M_\odot$ one has $M_1 > 0.51\ M_\odot$ and a > 6.7 × 10^{10} cm.

Here we note that the binary model predicts that the values of period derivative for the neutron star γ-rays and reprocessed companion X-rays will be almost the same, differing only slightly due to orbital period derivative. Then the negative γ-ray period derivative of ZM is in conflict with the positive X-ray period derivative of BCP. The low statistical reliability of the period derivatives is the likely cause of the conflict and is the reason for writing (Equation 1) with the parameter β.

The 1 solar mass companion is consistent with the optical observations of the 21.3 mag candidate for a solar type star (G0) if the distance is 2.9 kpc. For a companion of 0.5 $M_\odot$, the distance estimate is reduced to 700 pc. The Roche lobe is > 3 × 10^{10} cm, consistent with accretion onto a neutron star from an accretion disc. The accretion disc model of Ghosh & Lamb (1979) gives

$$\dot{P}/P = -6.1 \times 10^{-11}\, n(\omega_s) \mu_{30}^{2/7} (P/60 \text{ s}) L_{37}^{6/7}. \tag{4}$$

Here $n(\omega_s)$ is the dimensionless torque, ω_3 is the fastness parameter, μ_{30} is the magnetic moment in gauss cm^3 and L_{37} is the accretion luminosity in units of 10^{37} erg s^{-1}. The accretion luminosity is related to the γ-ray luminosity L_γ by the γ-ray production efficiency α:

$$L_{37} \times 10^{37} \text{ erg s}^{-1} = \alpha^{-1} L_\gamma = 1.9 \times 10^{35}\, d_1^2 \alpha^{-1} \text{ erg s}^{-1} \tag{5}$$

where d_1 is the distance in kpc. The fastness parameter ω_s depends on the mass, period, magnetic moment and mass accretion rate of the neutron star. Taking a 1.4 $M_\odot$ mass, 60 s period and the mass accretion rate required to produce the accretion luminosity, the fastness parameter is expressed as

$$\omega_s = 0.115\, \alpha^{3/7} d_1^{-6/7} \mu_{30}^{6/7}. \tag{6}$$

There are six parameters n, ω_s, μ_{30}, L_{37}, d_1 and α (assuming β is determined by the observations) but only four equations (4), (5), (6) and the n (ω_s) relation. Only limited restrictions on the parameters can be obtained in applying the model to 2CG 195 + 4. A rotating accreting neutron star is either a slow rotator ($n(\omega_s) > 0$) or a fast rotator ($n(\omega_s) < 0$), with $0 < \omega_s < 1$. Eliminatig L_{37} and μ_{30} from Equations (4), (5) and (6), we obtain for $P = 60$ s,

$$n(\omega_s) \cdot \omega_s^{1/3} = 11.7 \alpha \beta / d_1^2. \tag{7}$$

In the slow rotator case (low ω_s), $0 \leqslant n \leqslant 1.39$ and Equation (7) requires $\beta > 0$ and d_1 of the order of kpc or more. Taking $\beta = 1$ (the ZM period derivative) yields $d_1 = 5.4\ (1.39/n)^{7/12}\ \mu_{30}^{-1/6}\ \alpha^{1/2}$ kpc, with a weak dependence of distance on μ_{30}. If the values of μ_{30} and α are typical (1 and 0.1 respectively) then a distance of $\gtrsim 2$ kpc is implied in the slow rotator case. On the other hand, for the fast rotator case ($n < 0$), ω_s must be greater than 0.35 (Ghosh & Lamb 1979) which gives $d_1 < 0.27\ \alpha^{1/2}\ \mu_{30}$ kpc. For $\alpha = 0.1$, this gives an upper limit of 85 μ_{30} pc. For μ_{30} in the range 1 to 10, which is quite typical, a wide range of upper limits to distances (100–1000 pc) is allowed.

From the Einstein IPC data, Bignami, Caraveo & Lamb (1983) infer a low hydrogen column density ($N_H < 2 \times 10^{20}$ cm^{-2}) and an upper limit of 200 pc for the distance. It is well known that N_H towards the Crab nebula which is about 15° away from Geminga and at a distance of ~ 2 kpc, is 3×10^{21} cm^{-2} (Rappaport *et al*. 1969; Iyengar *et al.* 1975). However, it is interesting to observe that the contours of N_H in the solar neighbourhood, deduced from satellite ultraviolet observations (Frisch & York 1983) show a remarkable asymmetry with low neutral hydrogen densities in the quadrant $180° < l < 270°$. The contour corresponding to $N_H = 5 \times 10^{18}$ cm^{-2} corresponds to a distance > 200 pc in $180° < l < 270°$ whereas towards $l \sim 0$, it corresponds to distances < 15 pc. In the general direction of Geminga ($l = 195°$, $b = 4°$), N_H in the range of (5–10) × 10^{20} cm $^{-2}$ is indicated up to a distance of ~ 1 kpc. Drastic change in N_H in two directions (Crab and Geminga) 15° apart is not unlikely. Further, the low N_H in the direction of Geminga is, in principle, not inconsistent with a ~ 1 kpc distance if the density of the hot component of the interstellar medium which has a filling factor of 0.7–0.8 is 0.003 cm^{-3} (McKee & Ostriker 1977). It is essential to probe the density of neutral hydrogen in the direction of the particular line of sight towards Geminga to obtain a good estimate of the distance.

If we assume however, a distance of about few hundred pc for Geminga, we can rule out the slow rotator model. Equation (7) along with the constraints $0 < \omega_s < 1$ and $n < 1.39$, for $d_1 = 0.2$ and $\alpha = 0.1$, would imply a large negative value of n. This corresponds to $\beta < 0$ (spin down) and ω_s very close to the maximum value of 1. This conclusion emerges directly from Equation (4) as follows: for low distance (few hundred pc) L_{37} is low and to account for the large P/P, it is necessary to have a large $|n|$ which is possible only for $n < 0$. This makes $\omega_s \sim 1$, $\dot{P}/P > 0$ and hence $\beta < 0$ (Equation 1). It is believed that under such conditions unsteady accretion may occur (Ghosh & Lamb 1979).

Lastly, we consider the effects of having a pulse period of 30 s rather than 60 s. The binary (beat) period is then 3800 ± 600 s and the constants in Equations (2) and (3) are 2.1 (±0.2) × 10^{10} cm and 350 km s^{-1}. Since the expected width P^2/T_s of the χ^2 versus P curve is less, we may interpret the larger width of χ^2 versus P curve of BCP for the 1981 March 17–18 data as positive evidence for Doppler shifts. Then we obtain $M_1 \simeq 1 M_\odot$ for $M_2 = 1.4\ M_\odot$. The results of the accretion model are only changed slightly.

In conclusion, the period history of 2CG 195 + 4 is rather uncertain, partly due to the likely complication of binary Doppler shifts which have not been taken into account in the period analysis. Here we have pointed out the uncertainties and we have shown that a low-mass accretion binary at a distance of a few hundred pc, in which the neutron star is a fast rotator spinning down, is consistent with the current data. The separate question of the physical mechanism for generating the γ-ray emission has not been answered by any model yet. However, the high energy γ-ray source Cyg X-3 has a binary period of 4.8 hours similar to that proposed for 2CG 195 + 4.

Evidence presented here suggests the true pulse period is near 30 s. This should be further tested. The period analysis should be redone including binary motion to. determine if there is a positive or negative intrinsic P and to determine if $\dot{P}$ is changing. The determination of the period can be done more accurately by fitting the theoretical χ^2 versus P relation to the experimental data rather than picking the period with peak χ^2 (D. Leahy, in preparation). A repeat of the Čerenkov measurement would be valuable in determining the high energy behaviour. Finally, further optical observations will be valuable in verifying the nature of the companion and the distance to 2CG195 + 4.

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References

Bignami, G., Caraveo, P., Lamb, R.1983, *Astrophys. J. Lett.,* **272**, L9
Bignami, G., Caraveo, P., Paul, J. 1984, *Nature,* **310**, 464 (BCP).
Buccheri, R., D'Amico, N, Hermsen, W., Sacco, B. 1985, *Nature,* **316,** 131.
Caraveo, P., Bignami, G., Vigroux, L., Paul, J.1984, *Astrophys. J.*, **276**, L45.
Djorgovski, S., Kulkami, S. R. 1986, *Astr. J.*, **91**, 90.
Eadie, W., Drijard, D., James, F., Roos, M., Sadouet, B. 1971, *Statistical Methods* in Physics, North Holland, New York.
Frisch, P. C., York, D. G. 1983, *Astrophys. J.*, **271**, L59.
Ghosh, P., Lamb, F. 1979, *Astrophys. J.*, **234,** 296.
Halpern, J., Grindlay, J., Tytler, D. 1985, *Astrophys. J.*, **296**, 190.
Iyengar, V. S., Naranan, S., Sreekantan, B. V. 1975, *Astrophys. Space Sci.*, **32,** 431.
Leahy, D., Darbo, W., Eisner, R., Weisskopf, M., Sutherland, P., Kahn, S., Grindlay, J. 1983, *Astrophys. J.*, **266**, 160.
Masnou, J. L., Bennett, K., Bignami, G., Buccheri, R., Caraveo, P., D'Amico, N., Hermsen, W., Kanbach, G, Lichti, C. G., Mayer-Hasselwander, H. A., Paul, J. P., Swanenberg, B. N. 1977, In *Proc.* 12*th ESLAB Symp. Recent Advances in Gamma Ray Astronomy*, Ed. R. D. Wills & B. Battrick, p. 33.
Masnou, J. L., Bennett, K., Bignami, G. F., Bloemen, J. B. G. M., Buccheri, R., Caraveo, P. A., Hermsen, W., Kanbach, G, Mayer-Hasselwander, H. A., Paul, J. A., Wills, R. D. 1981, in *Proc*, 17*th Cosmic Ray Conf.* Paris, **1**, 177.
McKee, C., Ostriker, J.1977, *Astrophys. J.*, **218**, 148.
Rappaport, S., Bradt, H. V., Meyer, W. 1969, *Astrophys. J.*, **157**, L21.
Sol, H., Tarenghi, M., Vanderriest, C., Vigroux, L., Lelievre, G. 1965. *Astr. Astrophys.,* **144**,109.
Thompson, D., Fichtel, C., Hartman, R., Kniffen, D., Lamb, R. 1977, *Astrophys. J.*, **213**, 252.
Zyskin, Y., Mukanov, D.1983, *Soviet Astr. Lett.*, **9**, 117(ZM).