Classical spin-orbit coupling and periastron advance in a binary pulsar

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Abstract

We report on radio timing observations of PSR J0045-7319, an eccentric pulsar/B star 51-day binary in the Small Magellanic Cloud. Significant deviations from a simple Keplerian orbit, observed as precessions of the periastron longitude and orbital plane, are identified with classical spin-orbit coupling and apsidal advance, for the first time in a binary pulsar. Both precessions result from the B star's rotationally-induced gravitational quadrupole moment, however the orbital plane precession requires the B star's spin axis to be inclined with respect to the orbital angular momentum. We constrain this inclination angle 0 to 1)(! $25° < \theta < 410$. Under the conventional assumption that the pre-supernova angular momenta were aligned, our observations provide the most direct evidence yet for an asymmetric supernova.

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The radio pulsar PSR J0045−7319 was discovered in a systematic search of the Small Magellanic Cloud for pulsars [1]. It has a rotation period of 0.926 s and a flux density at 430 MHz of 1 mJy. Its binary nature was revealed after timing observations showed a regular 51-day variation in the observed barycentric periods, interpreted as Doppler shifts due to radial velocity variations [2]. The timing observations determined the binary parameters, showing that the orbit is highly eccentric and that the minimum companion mass, for an edge-on orbit, is 4 $M_\odot$. Optical observations reveal a 16th magnitude B star within the pulsar timing position error box. The association between the pulsar and B star has been confirmed by the detection of Doppler shifts of the companion's spectral lines at the expected orbital phase [3]. The amplitude of the B star's radial velocity variation determines the mass ratio in the system to be 6.3 ± 1.2. For a 1.4 $M_\odot$ neutron star [4], the B star's mass is $(8.8 \pm 1.8) M_\odot$, implying the orbital angular momentum vector is inclined by $44° \pm 3°$ with respect to the line of sight.

From the known system parameters, at periastron, the pulsar's distance from its companion is $(3.7 \pm 0.5) R_c$, while at apastron the separation is $(35 \pm 5) R_c$, where the companion radius, $R_c = (6.4 \pm 0.7) R_\odot$, is known from the optical observations [3]. Thus the pulsar allows us to sample very different lines-of-sight in the B star's vicinity. A stellar wind could result in variations of the electron column density with orbital phase. However no variation has been detected, setting an interesting constraint on the B star's mass-loss rate [5]. In the absence of electron column density variations, observed timing anomalies most likely have a dynamical origin.

A companion rotating at a velocity typical of B stars should have a substantial equatorial bulge, and hence there should be a significant quadrupole term in the gravitational potential. As a result, classical advance of the longitude of periastron, as well as spin-orbit coupling if the B star's spin axis is misaligned from the orbital angular momentum, should be detectable in the PSR J0045−7319 system [7]. Spin-orbit coupling results in a precession of the orbital plane, as both the orbital and spin angular momenta precess about the fixed total angular momentum vector, analogous to the precession of satellites in Earth orbit [8]. The quadrupole moment induced tidally by the neutron star (the "static tide") is expected to be much smaller than the rotationally-induced term [7].

We report here on timing data obtained for PSR J0045−7319 between 1991 February and 1995 October. A complete description of the observing system used at the 64-m Parkes radio telescope in NSW, Australia, as well as of our offline data processing procedures, is published elsewhere [5]. Our timing analysis includes a total of 231 arrival times obtained at 430 MHz, 660 MHz, and 1520 MHz, with typical pulse arrival uncertainties of 0.5–3.5 ms. A modified version of the standard pulsar timing analysis software package TEMPO [9] was used, along with the JPL DE200 ephemeris.

A "residual" is the time difference between an observed pulse arrival time and that predicted by the best available timing model for the pulsar. Residuals for PSR J0045−7319 after the subtraction of a model including only astrometric, spin, and Keplerian orbital parameters are shown in Fig. 1a. The rms residual is 19 ms, or 0.026 times the pulse period, much larger than our measurement uncertainties. Inspection of residuals plotted as a function of orbital phase (Fig. 1b), and indeed of neighboring residuals obtained in week-long sessions around periastron, reveals systematic trends in the data, rather than random variations [6].

Fig. 1c shows residuals plotted versus time after the subtraction of a model including the pulsar parameters shown in Table 1. The rms residual is 3.7 ms, or 0.004 times the pulse period. This timing model includes astrometric, spin, Keplerian orbital parameters, as well as a time-variable longitude of periastron ω, projected semi-major axis $x \equiv a \sin i$, and orbital period P_b. The significant values of $\dot{\omega}$ and $\dot{x}$ are expected from a rotationally-induced quadrupole, where $\dot{x}$ is interpreted as a varying inclination angle i, di/dt, with the semi-major axis a constant. Fig. 1d shows the residuals plotted as a function of orbital phase (Fig. 1d); they are featureless.

The best-fit parameters reported in Table 1 were found as follows. In order to minimize contamination of parameters by timing noise, the astrometric and orbital parameters were determined while fitting out sufficiently many spin period derivatives (six were required) to render the residuals Gaussian-distributed, in a manner similar to that used in other pulse timing analyses in the presence of red noise (e.g. Ref. [10]). Those parameters were subsequently held fixed when the spin parameters were fitted. The integrated electron column density was held fixed at 105.08 pc cm^{-3} throughout the analysis [5], and $\dot{e}$ was fixed at zero while determining all other parameters. The upper limit for $\dot{e}$ is at the 99% confidence level.

Experience has shown that standard analytical formulae (e.g. Ref. [11]) used in estimating pulse arrival time uncertainties can underestimate the true uncertainty by a factor of 2–3. Estimating uncertainties using the scatter in neighboring groups of arrival times introduces systematic biases that render the technique impractical for PSR J0045−7319. To handle this difficulty, we have worked under the assumption that the reduced χ^2 of the Gaussian-distributed residuals obtained while fitting out many spin period derivatives is unity. Under this assumption, the reduced χ^2 for the simple Keplerian model is 45 for 220 degrees of freedom, while that for the model in Table 1 is 1.5 for 217 degrees of freedom. The F-test shows the improvement in the fit after the addition of the three extra parameters is enormously significant; this statement holds even if the above assumption is relaxed. The parameter uncertainties in Table 1 are our best estimates of the 68% confidence limits determined using a bootstrap Monte Carlo technique [12].

The absence of systematic trends in the residuals, the low rms residual, and the significant drop in the χ^2 argue strongly that this timing model is correct. Indeed, a similar model obtained using arrival times up to 26 August 1995 predicts the remaining 27 arrival times obtained until 3 October 1995 to within 1.2% of the pulse period; from the beginning of the observations, the timing model includes terms that result in a phase offset of $\sim$150 ms by September 1995. In addition, the pulsar timing position given in Table 1 has an uncertainty reduced by a factor of four relative to that previously reported [2] while having moved closer to the optical position by a factor of three. Subdividing the arrival times into four year-long segments and performing local fits of the Keplerian parameters while holding $\dot{x}$, $\dot{\omega}$, and $\dot{P}_b$ fixed at zero confirms the tabulated results. The unusual appearance of the residuals in Fig. 1a and b is a result of biasing of the true orbital parameters by the neglect of any varying terms, exacerbated by the irregular data sampling. The value for $\dot{x}$ is of the wrong sign and is two orders of magnitude greater than what would be predicted from Kepler's laws and the observed $\dot{P}_b$, which is consistent with the varying i interpretation. The value for $\dot{\omega}$ reported here is about six times larger than the value expected from general relativistic (GR) precession. It is also somewhat larger than the upper limit previously reported [2];

the longer data span and the simultaneous fit for other varying orbital parameters account for the discrepancy.

The measured $\ddot{P}$ is much larger than that predicted from simple magnetic dipole braking and hence is probably not deterministic. Rather, it is most likely a manifestation of "timing noise" seen in most other pulsars having similar characteristics to PSR J0045- 7319. The fitted value for $\ddot{P}$ is consistent with that expected on the basis of the known empirical relationship between $\dot{P}$ and $\ddot{P}$ [13]. The slightly non-Gaussian quality of the residuals in Fig. 1c is likely to be a remnant of timing noise, and is the dominant contributor to the deviation of the reduced χ^2 from unity.

The observed values of $\dot{\omega}$ and $\mathrm{d}i/\mathrm{d}t$ can be used to constrain θ, the angle between the B star and orbital angular momenta, in three ways [7]. The rotationally-induced quadrupole model demands a precession of the longitude of periastron given by [14,7]

$$\dot{\omega} = \Omega_{\mathrm{orb}} \frac{k R_c^2 \hat{\Omega}_s^2}{a^2(1-e^2)^2} \left(1 - \frac{3}{2}\sin^2\theta\right), \tag{1}$$

and a precession of the orbital inclination angle

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \Omega_{\mathrm{orb}} \frac{k R_c^2 \hat{\Omega}_s^2}{a^2(1-e^2)^2} \sin\theta\cos\theta\sin\Phi, \tag{2}$$

where $\Omega_{\mathrm{orb}} = 2\pi/P_b$, $\hat{\Omega}_s = \Omega_s/(GM_c/R_c^3)^{1/2}$ (Ω_s is the companion angular velocity), k is the apsidal constant (e.g. Claret & Gimenez 1991), and Φ is the unknown orbital plane precession phase. First, from Equation 1 and noting from Table 1 that $\dot{\omega} > 0$, we have $\theta < 55^\circ$. The area to the right of the vertical dashed line in Fig. 2, in which we have represented the θ- Φ plane, is thus excluded. Second, from Equations 1 and 2, it is clear that the ratio $\dot{\omega}/(\mathrm{d}i/\mathrm{d}t)$ depends on θ and Φ only. Thus, the observed values for $\dot{\omega}$ and $\dot{x}$ establish a unique relation between θ and Φ, which traces a curve (the heavy solid line) in the θ- Φ plane (Fig. 2). The ratio conveniently eliminates any dependence on uncertain parameters such as $\hat{\Omega}_s$, k, and R_c. A correction for the expected GR contribution to $\dot{\omega}$ of 0.004° yr^{-1} was made before the ratio was taken. As the true values of θ and Φ must lie on the curve, θ is constrained to be larger than 25°. A third constraint on θ and Φ can be obtained using the observed B star rotational velocity [3], $v \sin i_c = (113 \pm 10)$ km s^{-1}, where i_c is the inclination angle of the B star's spin axis to the line of sight. By requiring that the B star be rotating less rapidly than the break-up velocity, $v < v_{\mathrm{break}} \simeq 420$ km s^{-1}, a constraint on i_c is obtained. There exists a unique relationship [7] among i, i_c, θ, and Φ, and, using the known value of i, this constraint can be represented by the dotted curve in Fig. 2. The area below the dotted curve is excluded, requiring $\theta < 41^\circ$. Thus, we have constrained the angle between the B star's spin axis and the orbital angular momentum to be

$$25^\circ < \theta < 41^\circ. \tag{3}$$

Retrograde B star rotation with respect to the pulsar's orbit is indistinguishable from prograde rotation from our data; the above angles should be subtracted from 180° in this case. A contribution to $\dot{\omega}$ of the same order as the GR correction is plausible from a static tide quadrupole induced by the neutron star [7]. This would raise the lower limit; for a contribution equal to the GR value, the lower limit is 29°. However, 25° is a hard lower limit corresponding to zero static. tide contribution; its statistical uncertainty includes contributions from the measurement uncertainties in $\dot{\omega}$, (li/elf, and the GR $\dot{\omega}$. The 3σ lower limit when accounting for all uncertainties is 23° and is indicated in Fig. 2 by a light, solid curve. The unknown true B-star break-up velocity dominates the uncertainty in the upper limit. A break-up velocity of 400 km s^{-1} gives an upper limit of 40°, while 500 km s^{-1} results in 43°.

Non-zero values of θ are expected in neutron star binaries if the neutron star receives a velocity "kick" at the time of the supernova explosion, changing the direction of the orbital angular momentum vector of the binary [16]. Our observations provide the strongest evidence yet that such kicks occur. It is difficult to constrain orbital parameters of the pre-supernova binary, as the progenitor system could have had a semi-major axis a_p anywhere between $a(1-e) < a_p < a(1+e)$, or in an even larger range if orbital evolution has taken place. Nevertheless the kick must have been at least $2\,V \sin\theta/2$, where V is the relative velocity of the neutron star progenitor and the B star before the explosion. Even if we assume a 5 $M_\odot$ pre-supernova star and the widest possible progenitor system, for no post-SN orbital evolution, the kick velocity was at least 60 km s^{-1}. The progenitor of PSR J0045- 7319 is more likely to have been a closer system, because of the higher survival probability of such systems in the presence of kicks. Thus the kick velocity obtained by PSR J0045- 7319 was probably at least 100 km s^{-1}. Much greater values are possible, as are retrograde orbits for very large kicks.

The significant negative $\dot{P}_b$ implies the orbit is decaying on a time scale of 500,000 yr. The origin of the decay is unclear. Mechanisms invoked to explain orbital decay observed in some high mass X-ray binaries (e.g. Levine et al. 1993) are not applicable in this main sequence star system. Oscillation modes in the B star excited dynamically by the pulsar orbit are expected to be damped in a time long compared to P_b [18,7], and hence should not result in a secular $\dot{P}_b$. Furthermore, it is surprising that the decay time scale, if $\dot{P}_b$ is stable, is much shorter than the pulsar's characteristic age $\tau = 3 \times 10^6$ yr, unless τ is not a good age indicator, and the pulsar was born with a spin period comparable to its present spin-period. Pulsars born with long-periods have been hypothesized by some synthesis studies [19]. Continued radio monitoring of the system to verify the stability of $\dot{P}_b$ is planned.

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FIGURES

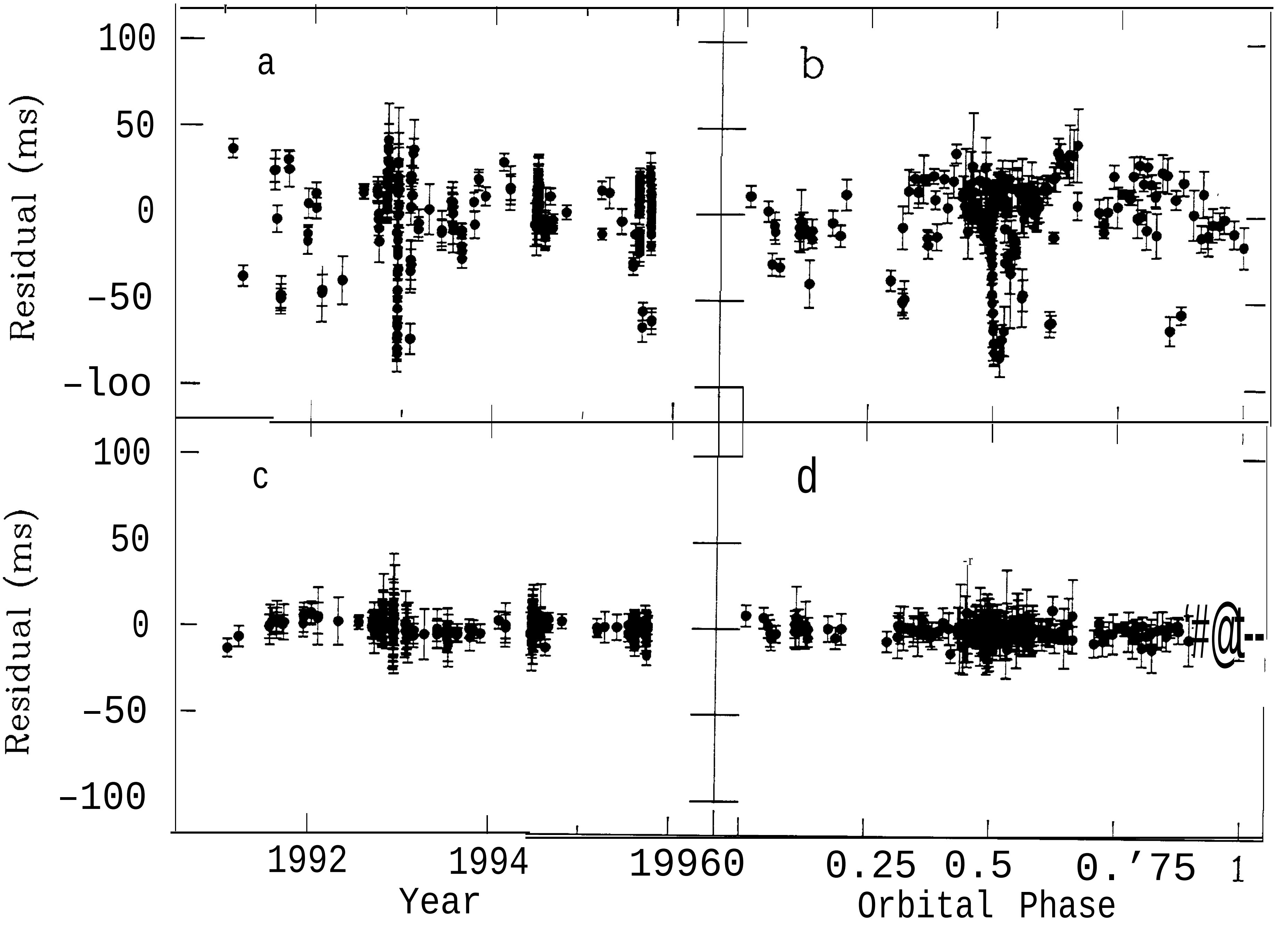
FIG. 1. Residuals for PSR J0045−7319 (a) after subtraction of a model including astrometric, spin, and Keplerian orbital parameters only. (b) Same residuals as in (a) but plotted versus orbital phase. (c) Residuals after subtraction of model parameters given in Table 1. (d) The same residuals as in (c) but plotted versus orbital phase.

FIG. 2. Observational constraints on the geometry of the PSR J0045−7319 binary system. See text for description.

TABLES

TABLE 1. Best-fit astrometric, spin, and orbital parameters for PSR J0045−7319.

Right Ascension, α (J2000)	$00^h\ 45^m\ 35^s.16 \pm 0^s.07$
Declination, δ (J2000)	$-73^\circ\ 19'\ 03''.0 \pm 0''.2$
Spin period, P	0,926275904972(27) s
Period derivative, $\dot{P}$	$4.4632(9) \times 10^{-15}$
Second period derivative, $\ddot{P}$	$-7.1(4) \times 10^{-25}\ s^{-1}$
Period epoch	MJD 49144.0000
Orbital period, P_b	4421040.6(4) s
Projected semi-major axis, $x \equiv a \sin i$	174.2576(7) lt s
Longitude of periastron, ω	115°.2540(5)
Eccentricity, e	0.807949(3)
Periastron epoch	MJD 49169,21361(3)
$\dot{\omega}$	$0^\circ.0259(5)\ yr^{-1}$
$\dot{x}$	$1.169(17) \times 10^{-9}$ lt s s^{-1}
$\dot{P}_b$	$-3.03(9) \times 10^{-7}$
$\dot{e}$	$< 2.2 \times 10^{-13}\ s^{-1}$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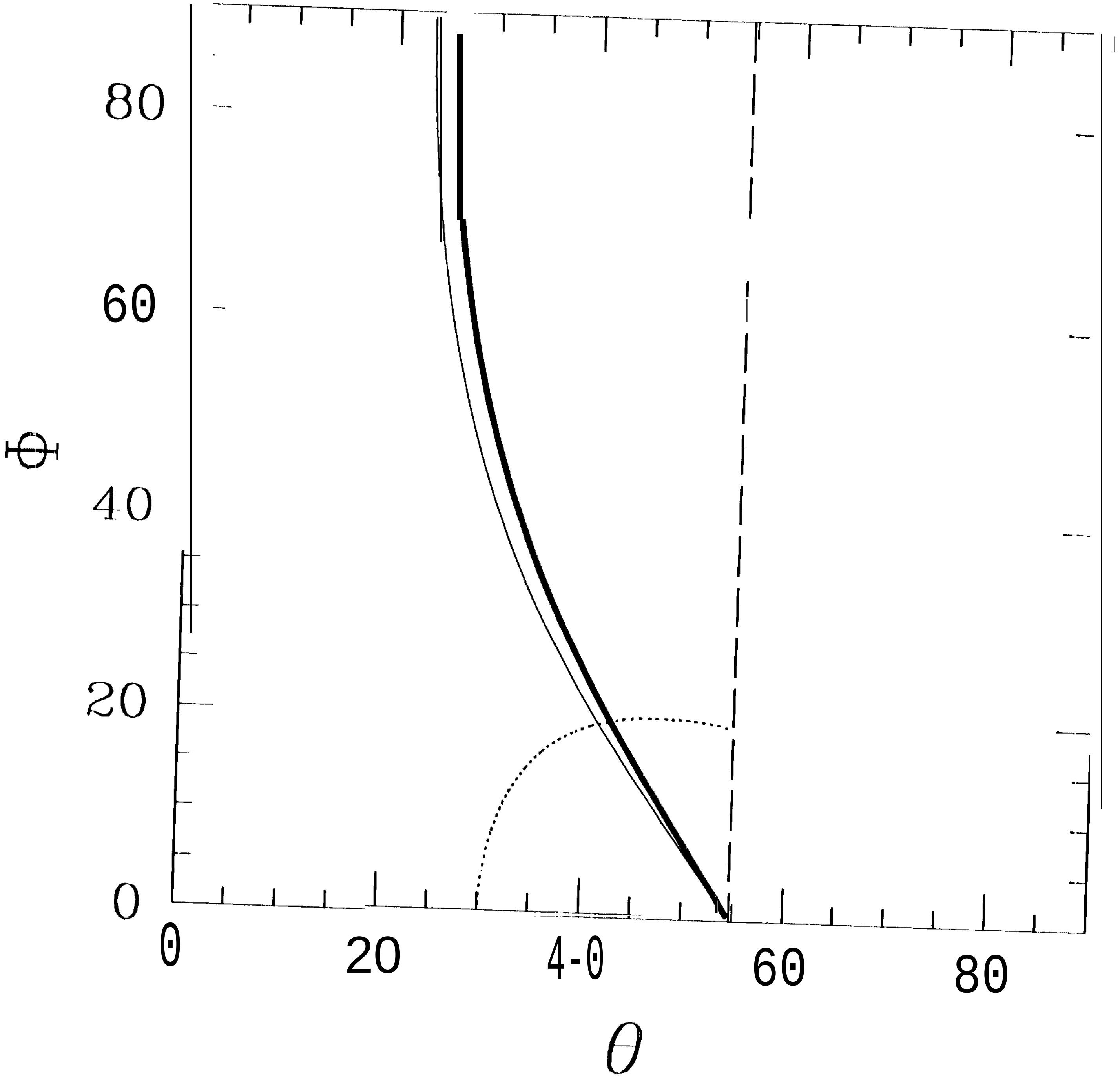
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