Dark Matter Constraints from the Eccentric Supermassive Black Hole Binary OJ 287

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OJ 287 is a blazar thought to be a binary system containing a $\sim 18$ billion solar mass primary black hole accompanied by a $\sim 150$ million solar mass secondary black hole in an eccentric orbit, which triggers electromagnetic flares twice in every $\sim 12$ year orbital period when it traverses the accretion disk of the primary. The times of these emissions are consistent with the predictions of general relativity calculated to the 4.5th post-Newtonian order. The orbit of the secondary black hole samples the gravitational field at distances between $O(10)$ and $O(50)$ Schwarzschild radii around the primary, and hence is sensitive to the possible presence of a dark matter spike around it. We find that the agreement of general-relativistic calculations with the measured timings of flares from OJ 287 constrains the mass of such a spike to $\lesssim 3\%$ of the primary mass.

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OJ 287 is an active galactic nucleus (AGN) situated near the ecliptic in the constellation of Cancer at a cosmological redshift $z = 0.3056$ [1, 2]. It is categorised as a BL Lacertae (BL Lac) object with a relativistic jet aligned very close to our line of sight [3]. Due to its proximity to the ecliptic, OJ 287 was often unintentionally photographed in the past, with an optical database dating back to 1888 [4–8], in addition to dedicated observing programmes [8–10]. This huge data set contains quasi-periodic pairs of electromagnetic flares every $\sim 12$ years [11], which are explained by Lehto and Valtonen [12, 13] as impacts of a secondary black hole (BH) with the accretion disk of the primary BH as it describes an eccentric orbit. These impacts occur during periapsis approach and retreat, and the intervals between the flares are modulated by the precession of the orbit and the emission of gravitational waves [14–16].

In this scenario, the secondary BH punches through the geometrically thin, optically thick and radiation-dominated accretion disk of the primary BH with hypersonic velocity, shocking gas and generating hot bubbles of plasma on each side of the disk that expand, cool down adiabatically and eventually radiate by thermal bremsstrahlung after becoming optically thin [12, 13], producing the observed flares [17]. The time delay between the emergence of a bubble at the impact site and the epoch when it becomes transparent is an important aspect of the binary BH model. While this can be estimated via detailed astrophysical modelling of the disk impact shock and outflow evolution [18], it necessarily introduces some uncertainty into the calculations.

The observations constrain the primary BH to have a mass $\sim 18.35 \times 10^9 M_\odot$ [15], with the secondary BH having a mass $\sim 150 \times 10^6 M_\odot$. The orbit of the secondary BH has an eccentricity of $\sim 0.65$, with a periastron $\sim 9$ and an apoapsis $\sim 48$ times the primary’s Schwarzschild radius, which is $\sim 360$ AU. These properties make OJ 287 a very powerful laboratory for probing general relativity (GR) and other aspects of fundamental physics. The GR predictions for the binary system have been calculated to 4.5th post-Newtonian order, including the dissipative effects of the emission of gravitational waves, and these calculations have been used to predict successfully the time of the 2019 burst of electromagnetic emission, which arrived within a few hours of the predicted time [15].

In this paper we use the successful comparison of GR predictions with the data on this unique astrophysical system to provide for the first time a constraint on physics beyond the Standard Model of particle physics, specifically on models of dark matter. It was argued in [19] that if cold dark matter is present at the centre of a galaxy, a massive central BH distributes it adiabatically into a ‘spike’ with a radial profile of the form

$$\rho(r) \propto F(r) \left(\frac{R_{sp}}{r}\right)^{\gamma_{sp}},$$

with $F(r) = (1 - 2R_{S}/r)^3$, where $R_{S}$ is the Schwarzschild radius of the BH, and $R_{sp}$ scales the size of the spike. (See [20, 21] for a critique of the possible existence of a spike.) The density slope parameter, $\gamma_{sp}$, is expected to lie between 2.25 and 2.5. The total mass of cold dark matter in the spike is obtained by integrating (1) over $r$ until the density sinks below the normal galactic dark matter density, and is unknown a priori because of the unknown normalisation of $F(r)$ that depends on the BH being considered and its environment.

Evidence for the existence of such a spike has been sought in the centre of the Milky Way. In particular, measurements of the orbit of the star S2, whose orbit samples the gravitational field of Sgr A* down to radii $\sim 10^{-2}$ pc, were found in [22] to constrain the spike mass to $\sim 1\%$ of the mass of Sgr A*, assuming $\gamma_{sp} = 7/3$ and $R_{sp} = 100$ pc, the upper limit obtained from VLT measurements of the orbit of S2. (A weaker constraint is provided by the concordance between the estimates of the mass of Sgr A* based on these orbital measurements and
the radius of the innermost stable circular orbit measured by the Event Horizon Telescope, $r_{\text{ISCO}} \simeq 50 \mu\text{as}$ [23], which requires that the spike mass be $\lesssim 10\%$ of the mass of Sgr A*.

The eccentricity of the orbit of the secondary BH in the OJ 287 system implies that it is sensitive to the density of any such spike around the primary BH at radii between the binary separations at periastron and apoastron, potentially causing deviations from the GR predictions. We use simulations to model these deviations and fit the OJ 287 data with modified parameters that include dark matter spikes of different magnitudes. We treat the gravitational effects of the spike in the Newtonian approximation, assuming that it is centred on the primary black hole and spherical, that shells with radii less than the separation between the primary and secondary have the same effect as a pointlike mass co-located with the primary, and that the effects of shells with radii larger than the separation can be neglected. We follow [22] in assuming $\gamma_{\text{sp}} = 7/3$, while we fix $R_{\text{sp}}$ at $5R_S$ (of the primary BH) throughout the analysis, and allow $\rho_{\text{sp}}$ to vary such that the total DM mass enclosed within a region $2R_S \lesssim r \lesssim 50R_S$ (encompassing the trajectory traversed by the secondary BH around the primary from periastron to apostron) equals the studied $m_{\text{sp}}/m_1$ ratio (ranging from 0 to 0.03). This is well within the gravitational radius of influence of the primary BH (defined as the radius at which the enclosed DM mass is twice the mass of the primary BH). We neglect dynamical friction and post-Newtonian effects due to the spike, which is justified a posteriori by the upper limit on its mass that we establish.

We use the Post-Newtonian (PN) scheme to calculate the orbital dynamics up to 4.5PN order. We work in the centre-of-mass (CoM) frame, converting the two-body problem to an effective one-body problem, and use harmonic coordinates. The harmonic condition, (de Donder gauge) is imposed, breaking general covariance. The relative two-body acceleration and the precessional dynamics of the spin of the primary, written in terms of the unit vector $\mathbf{s}_1$, can be estimated using

$$
\ddot{x} = \frac{d^2x}{dt^2} = \ddot{x}_0 + \ddot{x}_{1\text{PN}} + \ddot{x}_{2\text{PN}} + \ddot{x}_{3\text{PN}} + \ddot{x}_{2.5\text{PN}} + \ddot{x}_{3.5\text{PN}} + \ddot{x}_{4\text{PN}(\text{tail})} + \ddot{x}_{4.5\text{PN}} \ \ \ (2)
$$

where $x = x_1 - x_2$ is the CoM relative separation vector between the BHs with masses $m_1$ and $m_2$, $\ddot{x}_0 = -\frac{Gm}{r^3} \mathbf{x}$ is the zeroth-order Newtonian acceleration, where $m$ is the total mass of the binary and $r = |x|$, and $\mathbf{s}_1 = \frac{Gm_1^-}{c^2} \mathbf{x}$ is the spin of the primary with the Kerr parameter $\chi \in [0, 1]$ in GR. The terms $\ddot{x}_{\text{SO}}$ and $\ddot{x}_{\text{SS}}$ denote the spin-orbit (SO) and spin-spin (SS) couplings in GR, entering at 1.5PN and 2PN at leading orders, while $\ddot{x}_Q$ is the classical spin-orbit coupling (Q) arising from the quadrupole deformation of a Kerr BH, at 2PN order, and the $\Omega_i$ are the SO, SS and Q contributions to the precession of the primary BH spin vector. Our calculations of the various terms in (2) are based on an extensive body of work [24–29] and will be set out in detail in an upcoming publication.

The baseline binary BH model has 9 relevant parameters: the two BH masses $m_{1,2}$, the primary BH Kerr parameter $\chi_1$, the initial apocentre eccentricity $e_0$, the initial semimajor axis $a$ and its angle of orientation $\theta_0$, an ambiguity parameter $\gamma$ for the leading-order hereditary contributions to GW emission in the BBH dynamics implemented following Equation (5) in [15], an azimuthal angle $\varphi_{s1}$ and a polar angle $\psi_{s1}$ parametrising the orientation of the primary spin vector.

When making fits, the plane-crossing epochs must be corrected to incorporate astrophysical processes between an impact and an observed optical outburst, with a time delay $\tau_{\text{del}}$ added to account for the time lag between the generation of the plasma bubbles and the epoch at which they become optically thin. An additional timing correction $\tau_{\text{adv}}$ is applied to model the tidal force of the approaching secondary BH that warps the disk and advances the impacts. We adopt empirical models of the time delay and advance based on the best-fit orbit of [15], which our good fits resemble. In our orbital fitting procedure, the observational uncertainties are all assumed to be Gaussian and uncorrelated, and the optimisation algorithm adopted is the Nelder-Mead algorithm [30], which we implement using the constrNMpY package.

Fig. 1 displays the evolution of the OJ 287 system in our best no-DM fit over a period of 120 y, corresponding to 10 orbits of the secondary BH (represented by the smaller black spot), in a coordinate system centred on the primary BH (represented by the larger black spot). We see clearly the large orbital precession and the passages of the secondary BH through the accretion disc (represented as a shaded plane) as it approaches and retreats from the periastron.

Table I lists in the first column the starting times of flares of OJ 287 starting with that at the end of 1912, with the corresponding uncertainties shown in the second column. The timings of the flares not written in bold were not measured accurately and are not used in our fits. Ref. [15] used 10 flares, corresponding to 9 time differences that they fitted using the 9 parameters listed above. In our analysis we have one additional parameter characterizing the spike, and our fits include the well-measured 2019 flare as well as the less accurately measured flares in 1959 and 1994. The contribution of the spike to the dynamics is included at zeroth order and follows the mass profile obtained from (1). The third column in the Table lists the predictions for the starting times in our best-fit no-DM spike model, the fourth column is our best fit for
FIG. 1. The precessing orbit of the secondary BH (smaller black spot) in a coordinate system centred on the primary BH (larger black spot). Note the passages of the secondary BH through the accretion disc (represented as a shaded plane).

a spike mass ratio $m_{sp}/m_1 = 0.02$, and the fifth column is that for a spike mass ratio of 0.03.

Fig. 2 shows the minimum values of $\chi^2$ that we found for the indicated choices of the spike mass ratio, $m_{sp}/m_1$. The best-fit no-DM model has $\chi^2 = 6.05$, and the best fits for values of $m_{sp}/m_1 < 0.03$ all have $\chi^2 \lesssim 10$, corresponding to $p$-values $\gtrsim 20\%$. However, the best fit for $m_{sp}/m_1 = 0.03$ has $\chi^2 \simeq 13.6$, corresponding to a $p$-value $\simeq 3\%$, and the values of $\chi^2$ rise sharply as $m_{sp}/m_1$ increases beyond 0.03. For example, $\chi^2 \simeq 99$ already for $m_{sp}/m_1 = 0.035$, corresponding to a $p$-value $\simeq 10^{-18}$. On the basis of these results we conclude that the current OJ 287 data set an upper limit $m_{sp}/m_1 \lesssim 0.03$.

The upper panel of Fig. 3 compares the predictions of our best-fit models with no DM spike (shown as red spots), $m_{sp}/m_1 = 0.02$ (shown as blue crosses) and $m_{sp}/m_1 = 0.03$ (shown as purple triangles) with the observations (shown in black). We see a high level of consistency for the no-DM model, the most noticeable deviation being that for the 1994 flare. However, the observations of this flare were the least precise among the flares fitted, and its timing is the most uncertain, so we do not regard this deviation as being significant.

There is also a good level of consistency for the best fit with $m_{sp}/m_1 = 0.02$. However, the best fit with $m_{sp}/m_1 = 0.03$ clearly does not fit the data as well, enabling the eye to confirm the numerical analysis presented in the previous paragraph.

Our no-DM spike prediction for the very well measured 2019 flare shown in Table I agrees with the measured timing to within a few hours, within the uncertainty in the starting time of the 2019 flare. The timing of the 1982 flare is as well known as that in 2019, and our no-DM spike prediction for it again agrees with the measurement within a few hours.

As further support for our conclusion that $m_{sp}/m_1 \lesssim 0.03$, we have considered two possible side-effects of inter-

**TABLE I.** Starting epochs (in Julian years) of the observed optical flares of OJ 287 from 1912 onwards. First column: The data points prior to 1970 were obtained from archival photographic plates while the historical 1912/3 flare time is from [8]. We only use the flares listed in bold, the starting times of the other flares are not known accurately and are not used in the fits. Second column: The uncertainties in the starting times. Third, fourth and fifth columns: Our predictions for the starting times in the best-fit no-DM spike model and in the best-fit models with spike mass ratios of 2 and 3%.

| Julian year | uncertainty | No spike | 2% spike | 3% spike |
|------------|-------------|----------|----------|----------|
| 1912.980   | ±0.020      | 1912.982 | 1912.968 | 1912.958 |
| 1922.529   | -           | 1922.536 | 1922.537 | 1922.537 |
| 1923.725   | -           | 1923.730 | 1923.725 | 1923.722 |
| 1934.335   | -           | 1934.337 | 1934.340 | 1934.340 |
| 1935.398   | -           | 1935.403 | 1935.402 | 1935.400 |
| 1945.818   | -           | 1945.810 | 1945.822 | 1945.822 |
| 1947.283   | ±0.002      | 1947.285 | 1947.284 | 1947.283 |
| 1957.095   | ±0.025      | 1957.087 | 1957.078 | 1957.073 |
| 1959.25    | ±0.05       | 1959.216 | 1959.213 | 1959.213 |
| 1964.231   | -           | 1964.242 | 1964.216 | 1964.204 |
| 1971.126   | -           | 1971.129 | 1971.127 | 1971.127 |
| 1972.935   | ±0.012      | 1972.934 | 1972.921 | 1972.916 |
| 1982.964   | ±0.0005     | 1982.964 | 1982.965 | 1982.965 |
| 1984.125   | ±0.01       | 1984.120 | 1984.116 | 1984.114 |
| 1994.77    | ±0.1        | 1994.595 | 1994.599 | 1994.599 |
| 1995.841   | ±0.002      | 1995.839 | 1995.838 | 1995.838 |
| 2005.745   | ±0.015      | 2005.747 | 2005.754 | 2005.754 |
| 2007.691   | ±0.0015     | 2007.693 | 2007.691 | 2007.692 |
| 2015.875   | ±0.025      | 2015.882 | 2015.882 | 2015.872 |
| 2019.569   | ±0.0005     | 2019.569 | 2019.568 | 2019.569 |

FIG. 2. The dependence of the $\chi^2$ likelihood function on the ratio $m_{sp}/m_1$, as obtained from the sampling of model parameters described in the text.
actions between the secondary black hole and the spike. One is the dissipative effect of back-reaction on the orbit of the secondary black hole, and the other is the possible disruption of the spike by the secondary black hole. Following the approach of [32], we find that both effects can be neglected in a first approximation.

According to the model of [14–16] another flare of OJ 287 is expected shortly, though there are considerable astrophysical uncertainties in its timing, as discussed in [31]. We now discuss how the timing of this flare might differ from the no-spike pure GR case discussed in [31]. As seen in the lower panel of Fig. 3, our estimates for $m_{sp}/m_1 \lesssim 0.03$ suggest that the next flare might be advanced by $\lesssim 5$ days relative to the no-spike prediction. On the other hand, we estimate that it would be delayed by $> 10$ days for $m_{sp}/m_1 \geq 0.035$. In view of the uncertainty in the arrival time estimated in [31], our results suggest that observations of the next flare of OJ 287 may not be able to strengthen our constraint $m_{sp}/m_1 \leq 0.03$ based on the timings of previous flares.

GR has already been tested by observations of OJ 287 to the 4.5PN order, including the effects of GW emission [33], and will be tested again by observations of future flares. We have shown in the paper, for the first time, how observations of OJ 287 can be used to constrain models of new physics beyond the Standard Model of particle physics. Specifically, observations of OJ 287 can constrain the possible existence of a cold dark matter spike surrounding its primary BH. They already constrain the possible mass of such a spike to $m_{sp}/m_1 < 0.03$ at the 99.9% CL, and measurements of the timing of the expected future flares and more detailed modelling have the potential to constrain further the spike mass.

There are certainly ways in which the modelling of dark matter effects on the evolution of OJ 287 could be improved. For example, we have considered the possible static gravitational effects of a cold dark matter spike but have not considered other possible interactions between the secondary black hole and the spike, such as tidal forces or non-gravitational interactions. Another important area for future research will be to refine the modelling of the dynamical interactions between the secondary black hole and the accretion disk, and the time delay between the nominal impact on the accretion disk and electromagnetic emissions from the cooling of the plasma bubble that it generates, which is the dominant uncertainty in the prediction of the timing of any future flare.

OJ 287 has barely begun to demonstrate its potential for probing not just astrophysics and GR, but also other aspects of fundamental physics.

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