WEIGHING STELLAR–MASS BLACK HOLES WITH GAIA

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ABSTRACT

Stellar-mass black holes have been detected by radial-velocity observations in star/black hole binaries. These allow only the determination of the mass function. Tracking the astrometric orbits of the visible components of the star/black hole binaries would allow the full determination of the black hole masses, which would be of great astrophysical interest. We investigate the possibilities to do this with Gaia. A very promising object seems to be Cyg X-1. The donor star is an O9.7Iab supergiant having a mass of 25 $M_\odot$, and the mass of the black hole is estimated to be at least 13 $M_\odot$ masses. The period of 5.6 days implies a semi-major axis of 1.01 μpc of the binary orbit. At the distance of Cyg X-1 (2.5 kpc) this translates into a semi-major axis of about 28 μas for the visible component, which can be detected by Gaia. We discuss further candidates.

Key words: Stellar-mass black holes; Astrometric orbits; Gaia.

1. INTRODUCTION

Candidates for stellar–mass black holes have preferentially been found as X-ray sources in binary systems by radial velocity measurements of the optically visible companion star. Such measurements allow, however, only the determination of the mass functions

$$f(M) = \frac{P a_{RV}^3}{2\pi G} = \frac{M_{BH}^3 \, sin \, i^3}{(M_{BH} + M_*)^2} \,, \qquad (1)$$

where P denotes the orbital period, a_{RV} is the semi amplitude of the companion star's radial velocity curve and G is the constant of gravity. M_{BH} and M_* are the masses of the black hole and the companion star, respectively. i denotes the inclination of the orbital plane to the line of sight in the sense that $i = 90°$, if the orbit is seen edge-on. The inclination angle is not known from the radial velocity curve. If the latter is combined with the light curve and a measurement of the projected rotational velocity broadening of the spectral lines of the companion star, i can sometimes be estimated indirectly (Orosz 2003). A direct, much more accurate determination of the mass of

the black hole is possible, if the orbit of the companion star is observed also astrometrically. A precise measurement of the black hole mass would help to constrain the radius of the last stable orbit around the black hole. If the orbital period of material on such an orbit can be identified by intensity fluctuations of the system, this would be a physical experiment of great significance, because it would prove the existence of event horizons and allow the measurement of the spin parameter of the black hole.

2. THE CANDIDATE CYG X-1

We have examined the objects given in the compilations of Orosz (2003) and Tanaka & Lewin (1995) and tested whether the orbits of the companion stars can be observed with Gaia. We have found five objects for which the semi-major axis of the astrometric orbits exceed 10 μas, although four of them seem to be too faint to be actually measured by Gaia. Orbits of these four could in principle be detected by the SIM space interferometer, but would require a very significant amount of observing time. The parameters of the systems as well as distances and mass estimates for the black holes have been adopted from Orosz (2003), Tanaka & Lewin (1995) and references therein and are given in Table 1 for the five objects. The semi–major axis of the relative orbit of the black hole and companion star, $\vec{r}_* - \vec{r}_{BH}$, has been calculated with Kepler's law

$$4\pi^2 a_{*-BH}^3 = GP^2(M_* + M_{BH}) \,, \qquad (2)$$

and then converted to the *observable* semi-major axis of the orbit of the companion star projected onto the sky using the relation

$$a_* = \frac{1}{d} \frac{M_{BH}}{M_* + M_{BH}} \, a_{*-BH} \,, \qquad (3)$$

where d denotes the distance of the system from the Sun. In Equation 3 we assume that the accretion disc around the black hole is optically much fainter than the star.

We conclude from Table 1 that the orbit of the companion star HD 226868 of Cyg X-1 should be observable accurately with Gaia. In addition to the astrometry, high resolution spectroscopy of the companion star is required in order to verify the assumption that the disc is faint: The

Table 1. Black hole and companion star parameters

	V mag	sp.t.	M_* $M_\odot$	d kpc	P d	M_{BH} $M_\odot$	i deg	a_* μas
Cyg X-1	9	O9.7 Iab	25	2.5	5.6	13	35	28
V1003 Sco = GRO J1655-40	17	F6 III	2.4	3.5	2.6	6.3	70	16
V616 Mon = A 0620-00	18	K4 V	0.7	1.2	0.32	11	41	16
V404 Cyg = GS 2023+338	19	K0 IV	0.7	3.0	6.5	12	56	50
V381 Nor = XTE J1550-564	20	K3 III	1	3[†]	1.5	10	72	18

[†]distance very uncertain

spectral energy distribution will reveal emission from the disc. Furthermore, light reflected from the accretion disc can be detected and measured by Doppler–shifted binary spectral lines, because the star and the black hole move in opposite directions. Such a contamination is not expected for Cyg X-1. However, in some of the transient X-ray sources light from the disc could significantly contribute to the system's total light. The astrometric data must then be reduced as described by Wielen et al. (2000).

In the present paper we discuss only those nearby stellar black-hole candidates that are already known. However, Gould and Salim (2002) point out that there is a possibility that Gaia will find many more, if the (presently hypothetical) 'failed supernovae' – i.e., massive stars that directly collapse to black holes instead of exploding – do indeed occur.

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