Constraining the parameters of binary systems through time-dependent light deflection

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Abstract A theory is derived relating the configuration of the cores of active galaxies, specifically candidates for presumed super-massive black hole binaries (SMBHBs), to time-dependent changes in images of those galaxies. Three deflection quantities, resulting from the monopole term, mass quadrupole term, and spin dipole term of the core, are examined. The resulting observational technique is applied to the galaxy 3C66B. This technique is found to under idealized circumstances surpass the technique proposed by Jenet et al. in accuracy for constraining the mass of SMBHB candidates, but is exceeded in accuracy and precision by Jenet’s technique under currently understood likely conditions. The technique can also under favorable circumstances produce results measurable by currently available astronomical interferometry such as very-long-baseline interferometry (VLBI).

Keywords Light deflection · SMBHB · 3C66B · VLBI

1 Introduction

The deflection of light by gravity is the oldest experimentally verified test of the theory of general relativity [1]. With the continued improvement in observational resolution in astronomy, particularly through very-long-baseline interferometry (VLBI), the detection of more subtle effects of this light deflection becomes practical. Consequently, light deflection can be used to measure the properties of distant systems. This paper supplies a theory for using time-variable light deflection to measure or constrain the parameters of binary systems. Specifically, the deflection angle of a light ray from a
distant source is related to the configuration and motion of a binary system located in a distant galaxy somewhere between the point of emission of the light ray and its observation.

Super-massive black hole binaries (SMBHBs) are thought to form the cores and primary energy sources of the broad class of galaxies termed “active galaxies”, “blazars”, or “quasars”. However, a combination of distance, radio noise, and optical thickness makes direct observation of presumed SMBHBs impractical. Observing a time-dependent motion in the image of the galaxy can provide information on the mass and orbital parameters of an SMBHB candidate.

Work by Damour and Esposito-Farese [6] and by Kopeikin et al. [5] establishes a theory of time-dependent light deflection by describing the time-dependent part of the deflection through the quadrupole term, which is the lowest-order term resulting from the mass distribution whose effects are practical to evaluate using current astronomical observational techniques. The work of Mashhoon and Kopeikin [25] in examining gravitomagnetic effects furthermore provides a theory for evaluating the contribution of the spin dipole of such systems and complements the work of Einstein [27] in providing a complete theory for stating the location of the deflected image, in the weak field limit. We generalize these theories to a stronger-field regime and put constraints on the theory’s applicability in this regime.

As a case study of an active galaxy, the theory is applied to the galaxy 3C66B, a nearby active galaxy with a candidate SMBHB core [13], and theoretical constraints on 3C66B’s parameters from a light deflection experiment are compared to the constraints claimed by Jenet et al. [2].

2 Theory

2.1 Notations, definitions and assumptions

We assume that Einstein’s theory of general relativity is true to the limits of our ability to observe and applicable to the systems under examination. We do not address MOND or other post-Einsteinian models.

Throughout this paper, “emitter” refers to the source of light rays being observed; “deflector” refers to the mass distribution causing a change in the metric of spacetime from flatness; and “observer” refers to the point where the light rays produced by the emitter are observed.

We also make use of a coordinate system derived from the Cartesian system, defined thus: in a space that is asymptotically Cartesian let a line be described by

\[ x^i \left( t \right) = k^i \left( t - t_0 \right) + x^i_0. \] (1)

Let \( t^* \) be the time associated with the line’s closest approach to the origin of the Cartesian system. Let \( \tau = t - t^* \) denote a new time coordinate (that is, at \( \tau = 0 \)

1 Throughout this paper, Greek indices indicate \((0, 1, 2, 3)\) and Latin indices indicate \((1, 2, 3)\). A contravariant 3-vector is denoted either in boldface or with a raised Latin index.