

# Explaining the light curves of gamma-ray bursts with a precessing jet

S.F. Portegies Zwart<sup>1,2,\*</sup>, C.-H. Lee<sup>3</sup>, and H.K. Lee<sup>3,4</sup>

<sup>1</sup> Boston University, Department of Astronomy 725 Commonwealth Avenue, Boston, Massachusetts 02215, U.S.A.

<sup>2</sup> Department of Information Science and Graphics, College of Arts and Science, University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153, Japan

<sup>3</sup> Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, NY 11794, U.S.A.

<sup>4</sup> Department of Physics, Hanyang University, Seoul 133-791, Korea

Received January 21; accepted March 17, 1999

**Abstract.** A phenomenological model is presented to explain the light curves of gamma-ray bursts. Gamma-rays are produced in a narrow beam which sweeps through space due to the precession of a slaved accretion disc. The light curve expected from such a precessing luminosity cone can explain the complex temporal behavior of bright gamma-ray bursts.

**Key words:** accretion discs — black hole physics — binaries: close — stars: neutron — gamma-rays: bursts — gamma-rays: theory

## 1. Introduction

Gamma-ray bursts are observed with a large variety in duration, ranging from seconds to minutes (Norris et al. 1996), intensity and variability. The shortest temporal structures are unresolved by detectors and reflect the activity of a highly variable inner engine (Fenimore et al. 1996). On the other hand some bursts last for several minutes which indicates that the energy generation within the burst region has a rather long time scale.

In the proposed model a neutron star transfers mass to a black hole with a mass of 2.2 to 5.5  $M_{\odot}$ . A strong magnetic field is anchored in the disc, threads the black hole and taps its rotation energy via the Blandford-Znajek (1977) mechanism. Gamma-rays are emitted in a narrow beam. The luminosity distribution within the beam is given by the details of the Blandford-Znajek process. Precession of the inner part of the accretion disc causes the beam to sweep through space. This results in repeated pulses or flashes for an observer at a distant planet.

*Send offprint requests to:* S.F. Portegies Zwart  
e-mail: spz@grape.c.u-tokyo.ac.jp

\* Hubble Fellow.

This model was proposed by Portegies Zwart et al. (1999, hereafter PZLL) to explain the complex temporal structure of gamma-ray bursts.

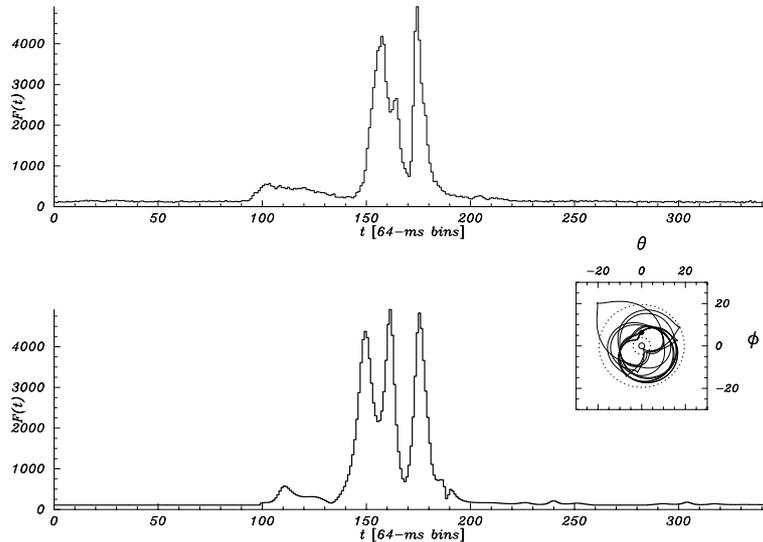
## 2. The gamma-ray binary

We start with a close binary where a low-mass black hole is accompanied by the helium star. The configuration results from the spiral-in of a compact object in a giant, the progenitor of the helium star (see Portegies Zwart 1998, hereafter PZ).

The collapse of the helium core results in the formation of a neutron star. The sudden mass loss in the supernova and the velocity kick imparted to the neutron star may dissociate the binary. If the system remains bound a neutron star – black hole binary is formed.

The separation between the two compact stars decreases due to gravitational wave radiation (see Peters & Mathews 1963). At an orbital separation of a few tens of kilometers the neutron star fills its Roche-lobe and starts to transfer mass to the black hole. Mass transfer from the neutron star to the black hole is driven by the emission of gravitational waves but can be stabilized by the redistribution of mass in the binary system. If the mass of the black hole  $\lesssim 2.2 M_{\odot}$  coalescence follows within a few orbital revolutions owing the Darwin-Riemann instability (Clarck et al. 1977). If the mass of the black hole  $\gtrsim 5.5 M_{\odot}$  the binary is gravitationally unstable (Lattimer & Schram 1976); the event horizon of the hole is then larger than than the orbital separation. Only in the small mass ranges from 2.2  $M_{\odot}$  to 5.5  $M_{\odot}$  stable mass transfer is possible (see PZ).

The entire episode of mass transfer lasts for several seconds. Mass transfer becomes unstable if the neutron star starts to expand rapidly as soon as its mass drops below the stability limit of  $\sim 0.1 M_{\odot}$ . Initially the neutron star's material falls in the black hole almost radially but



**Fig. 1.** The upper panel gives the flux (Y-axis) as a function of time (X-axis) for the gamma-ray burst with BATSE trigger numbers 1609. The lower panel gives the result of the fitted burst. Time is in units of 64 ms, the time resolution of BATSE. The upper right corner gives a schematic representation of the central locus of the black hole (central  $\circ$ ) and the trajectory of our line of sight (solid line) starting at the  $\bullet$ , moving clockwise. The inner dotted line identifies the angle at which the luminosity distribution within the luminosity cone is maximum, it drops to zero at the outer dotted line (see PZLL98) The simulated burst is binned in 64 ms bins to make a comparison with the observation more easy

at a later stage an accretion disc can be formed (see PZ for details).

### 3. The precessing jet

The asymmetry in the supernova, in which the neutron star is formed, causes the angular momentum axis of the binary to make an angle  $\nu$  with the spin axis of the black hole. This misalignment causes the accretion disc around the black hole to precess (see Larwood 1998).

The magnetic field of the black hole is anchored in the disc. Energy can then be extracted from the black hole by slowing down its rotation via the magnetic field which exerts torque on the induced current on the black hole horizon (Blandford & Znajek 1977; Thorne et al. 1986). The radiation is liberated in a narrow beam with an opening angle of  $\lesssim 6^\circ$  (Fendt 1997). Such a narrow beaming is supported by the results of the ROTSE (Robotical Optical Transient Search Experiment) telescope (see <http://www.umich.edu/rotse/> for more details). Since the magnetic field is anchored in the disc the radiation cone precesses with the same amplitude and period as the accretion disc.

The intrinsic time variation of a single gamma-ray burst has a short rise time followed by a linear decay (Fenimore 1997). We construct the burst time profile from three components: an exponential rise, a plateau phase and a stiff decay (see PZLL for details). Rapid variations within this timespan are caused by the precession and nutation of the beam. This results in a model with eight free parameters; three timescales for the profile of the burst, the precession and nutation periods, the precession angle

and the direction (two angles) from which the observer looks at the burst.

Figure 1 gives the result of fitting the model to the gamma-ray burst with BATSE trigger number 1609 in the energy channel between 115 keV and 320 keV. The fit was performed by minimizing the  $\chi^2$  with simulated annealing (see PZLL). The light curves computed with this model show similar complexities and variability as observed gamma-ray bursts (see Fig. 1).

*Acknowledgements.* We are grateful to Gerry Brown and Jun Makino for a great time, numerous discussions and financial support. This work was supported in part by the U.S. Department of Energy under Grant No. DE-FG02-88ER40388 and by NASA through Hubble Fellowship grant #HF-0112.01-98A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS 5-26555.

### References

- Blandford R.D., Znajek R., 1977, MNRAS 179, 433
- Clark J.P.A., Eardley D.M., 1977, ApJ 215, 311
- Fendt C., 1997, A&A 319, 1025
- Fenimore E.E., 1997, astro-ph/9712331
- Fenimore E.E., Madras C.D., Nayakshin S., 1996, ApJ 473, 998
- Larwood J.D., 1998, MNRAS 299, L32
- Lattimer J.M., Schram D.M., 1976, ApJ 210, 549
- Norris J.P., Nemiroff R.J., Bonnell J.T., et al., 1996, ApJ 459, 393
- Peters P.C., Mathews J., 1963, Phys. Rev. D 131, 345
- Portegies Zwart S.F., 1998, ApJ 503, L53, PZ
- Portegies Zwart S.F., Lee C.-H., Lee H.K., 1999, ApJ 520 (astro-ph/9808191), PZLL
- Thorne K., Prince R., MacDonald D., 1986, Black Holes. The membrane paradigm, Yale Univ. Press