Implication of the discovery of the proper motion of the optical counterpart of GRB 970228 for the models of gamma-ray bursts

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ABSTRACT
The accurate position determination of GRB 970228 by the Beppo/SAX Satellite led to the discovery of a fading X-ray and optical counterparts of the burst. About a month after the GRB event the proper motion of the ejecta was detected and the extended optical source has faded below the Keck detection level. We analyze these observations in the framework of the most popular gamma ray burst models. We find a lower limit on the distance to GRB 970228 \( d > 6.6 \) pc. We estimate the amount of energy required to explain the motion of a point source and the variability of the extended source. We find that the cosmological models are ruled out. The Galactic corona models suffer difficulties if the distance to the burst is \( > 100 \) kpc or the variability of the extended source is directly connected with the burst. No constraints are found for GRBs originating between \( 6.6 \) pc and \( \sim 10 \) kpc.

Key words: gamma-rays: bursts- X-rays: transients - optical: transients - stars:neutron

1 INTRODUCTION
Almost three decades after their discovery (Klebesadel et al. 1973) the origin of the gamma ray bursts (GRBs) is still under debate (Paczyński 1995; Lamb 1995). The cosmological distance scale was strongly suggested by the high degree of isotropy of GRB distribution measured by BATSE, as well as by the roll-over in the brightness distribution (Meegan et al. 1995). It has been shown that both these features can also be reproduced by galactic corona models invoking high velocity neutron stars (Bulik & Lamb 1995a; Bulik & Lamb 1995b; Li, Duncan & Thompson 1993). Some authors also entertain the idea of GRBs originating from the Oort cloud (Bickert & Greiner 1992).

The break-through in this field came with the detection of the burst GRB 970228 on February 28, 1997 by a new Italian-Dutch satellite Beppo/SAX (Costa et al. 1997a). A fast and accurate measurement of the source position with the X-ray camera yielded an error box only \( \sim 2 \) arcmin across (Costa et al. 1997b). This has been followed by numerous optical observations, and a detection of an optical variable (Groot et al. 1997a). Next came a report of a discovery of an extended source (Groot et al. 1997b) at the position of the optical transient, suggesting a distant galaxy as a source of the GRB event (Paradijs et al. 1995). This discovery was soon confirmed by the HST observation on March 26 (Sahu et al. 1997a), which has shown the existence of a point source and an extended component. A subsequent HST observation has been performed on April 7 (Sahu et al. 1997b). An attempt to obtain the redshift of the extended object using Keck telescope yielded a spectrum with no identifiable lines (Tonry et al. 1997). Analysis of the light curves in different wave bands show that emission follows \( \approx t^{-1} \) (Reichart 1997) which has been found to be consistent with a relativistic fireball afterglow (Wijers & Mészáros 1997).

A comparison of the two Hubble observations has shown that the point object has a significant proper motion of \( \approx 540 \) mas year\(^{-1}\) (Caraveo et al. 1997). Furthermore, it has been reported (Metzger et al. 1997) that the extended source has faded below detection limit in the R band using the Keck telescope on April 5 and 6, indicating also a variability on a 0.5" scale, and undermining the identification of the extended object with the host galaxy.

In this paper we discuss the direct implications of these observations on the gamma-ray burst distance scale and their models. In section 2 we derive a lower limit on the distance to GRB 970228 from the parallax and define distances for which relativistic effects are important, in section 3 we discuss the galactic corona models. In section 4 we
Although the amplitude of the velocity (\( \sim \)) motion of the Earth is improbable. It is difficult to suspect that the two independent movements might simply cancel. The possibility that gamma ray burst are very local phenomenon is not frequently discussed since there is no specific suggestion of how the gamma rays may actually be produced in the result of, for example, the cometary collisions. Also the present knowledge about the structure of the Oort cloud does not seem to be in agreement with the statistical properties of gamma bursts (Maoz 1973). However, the conclusion of that study was not firm so in any case it is interesting to consider the lower limit for the distance to the source which can be derived from the discovered proper motion.

If the source is really as close to the Earth as the Oort cloud its apparent motion consists of two components: (i) proper motion and (ii) the effect of parallax due to the orbital motion of Earth. The second effect is unavoidable and it is difficult to suspect that the two independent movements might simply cancel.

The source is located at R.A. = 5h01m44s, Decl. = +11\( ^\circ \)46\( ^\prime \)7. Therefore the angle \( \theta_{V-GRB} \) between the orbital motion of the Earth and the direction to GRB 970228 is only \( \theta_{V-GRB} \approx 23.8^\circ \) on March 26. The component of the Earth velocity perpendicular to the direction towards the source is equal \( V_{Earth} \sin \theta \).

The observed variability of the observed counterparts: the moving point source and the fading extended object introduces characteristic regimes in the distance scales. The proper motion of the point source on the sky is \( 0.54^\circ \) year\(^{-1} \). The inferred linear velocity perpendicular to the line of sight is

\[
v_{\perp}^{\text{ps}} \approx 10^{-5} \frac{D}{\text{1pc}} c.\tag{3}\]

Thus the distance at which the apparent velocity of the point source on the sky reaches the speed of light is \( D_1 = 100 \text{ kpc} \). The angular size of the extended source is \( \approx 0.5^\circ \), and we take a conservative assumption that it varies on the timescale of a month. A typical apparent linear velocity i.e. the ratio of the linear size to the observed variability scale is

\[
v_{\perp}^{\text{ex}} \approx 10^{-4} \frac{D}{\text{1pc}} c.\tag{4}\]

This define a distance at which \( v_{\perp}^{\text{ex}} = c \), so \( D_2 = 10 \text{ kpc} \).

We can now consider three regions in the space of possible distance to GRB 970228: A. the nonrelativistic region \( D < D_2 \). B. the mildly relativistic region \( D_2 < D < D_1 \) and C. the relativistic one \( D_1 < D \). It should be noted that regions B and C are not automatically excluded since apparent superluminal motion can be observed due to relativistic beaming. The apparent motion of the ejecta as projected on the sky proceeds with the velocity

\[
v_{\perp} = \frac{c \beta}{1 - \beta \cos \theta} \sin \theta \approx c \Gamma,\tag{5}\]

where \( \theta \), the angle between the ejecta axis and the line of sight, is taken \( \approx 1/\Gamma \).

### 2.2 Characteristic scales

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### 3 Galactic halo distances

In the framework of these models GRBs originate from high velocity neutron stars, with characteristic velocities \( \sim 1000 \text{ km s}^{-1} \). Such objects would leave the Galactic plane (the escape velocity from the Galaxy is \( \sim 600 \text{ km s}^{-1} \)) and form a Galactic corona (Lamb 1995; Li & Dermer 1992). Observations of isotropy of gamma-ray burst distribution on the sky (Macgibbon et al. 1993) provide a strong constraint on the distance to a typical burst. This constraint can be consistent only with models characterized by strong source evolution (also called the delayed turn-on, furthermore DT) or within the beaming model (Li & Dermer 1992) where the bursting direction is aligned with the direction of the initial kick velocity, furthermore BM. The isotropy constrains the beaming angle to be \( 15^\circ < \theta_b < 25^\circ \) (Bulik & Lamb 1995) [Duncan & Li 1997]. The estimates of the distance to the farthest burst seen by BATSE varies from 80 kpc to 350 kpc (Duncan & Li 1997; Bulik & Lamb 1995). Physical models of gamma ray bursts in the Galactic corona invoke magnetic instabilities in super magnetic neutron stars (Duncan & Thompson 1992; Podsiadlowski, Rees & Ruderman 1993; Lamb, Bulik & Coppi 1995), or accretion of a planetaeleon on a neutron star (Colgate & Leonard 1993). Within the framework of each of the scenarios a blast wave or a jet can follow a gamma ray burst event.
Since GRB 970228 was a relatively bright burst we assume that it is located at the distance of 100 kpc or less, i.e. in the mildly relativistic region. This estimate of $\Gamma$ depends, of course, on the assumed distance and varies from $\approx 1.1$ for the distance of 50 kpc, 1.9 for 100 kpc to $\approx 3$ for 300 kpc. The variability of the extended source requires Lorentz $\Gamma$ factors in the range from 5 to 30.

Given the above calculated value of $\Gamma$ we can estimate that the extent of the visible emission of the jet comes from the angle smaller than $\Gamma^{-1} \approx 30^\circ$. Assuming that the visible jet is directly associated with the gamma-ray burst we immediately obtain that if the expansion is isotropic we only see a fraction $f = 0.25\Gamma^{-2} \approx 0.06$ of the emitting surface. However, since the source is moving we know that the expansion is not spherical. In the framework of the DT model this places an interesting limit, requiring that there is $4\Gamma^{-2} \approx 16$ times more sources of the galactic corona GRBs or that they burst 16 times more often. Such a limit does not arise within the framework of the BM model proposed by Duncan & Thompson 1992 since the direction of emission is not randomly oriented. It has to be also noted that we find a tantalizing agreement of two numbers: the estimated angular width of the jet ($30^\circ$) and the beaming angle required by the isotropy of the BATSE bursts ($15^\circ - 25^\circ$) in the framework of this model.

The optical transient has been observed for $\Delta t_{\text{obs}} \approx 1$ month. In this time the ejecta must have traveled a distance of

$$r \approx c\Delta t_{\text{obs}}\Gamma^2 \approx 10^{17}\Gamma^2 \text{ cm}.$$  

A relativistic shock collects matter which slows it down while ploughing through space. The amount of matter collected by the ejecta can be estimated as

$$\Delta M = \frac{\pi}{3}\alpha^2 r \rho \approx \alpha^2 r \rho,$$  

where $\alpha = \Gamma^{-1}r$ is the perpendicular size of the cone sweeping by the ejecta. Thus we obtain $\Delta M = 10^{34}\Gamma^3(\rho/1\text{ g cm}^{-3})$ g. A relativistic shock will be efficiently decelerated if it collides with a mass $\Delta M > m_e \Gamma^{-1}$ where $m_e$ is the mass of the ejecta. Thus we obtain a constraint on the mass of the ejecta

$$m_e > \Delta M \Gamma = 10^{34}\Gamma^5(\rho/1\text{ g cm}^{-3}) \text{ g}.$$  

The energetic requirement for a burst source to accelerate $m_e$ to a Lorentz factor $\Gamma$ is

$$E \approx m_e c^2 \Gamma > 10^{42}\Gamma^6 \frac{\rho}{10^{-30}\text{ g cm}^{-3}} \text{ erg},$$  

where we scaled the density to a typical value for the intergalactic space.

For the expected range of $1 < \Gamma < 3$ for the motion of the point source these models are on the edge of viability with energetic requirement varying from a comfortable $10^{42}$ ergs to rather constraining $10^{46}$ ergs. The variability of the extended source increases these requirements by a factor of at least $10^6$ and up to $10^9$. Note that the above estimates are very conservative since the density in the Galactic halo can be higher.

4 EXTRAGALACTIC ORIGIN

Cosmological origin of GRB explains in a natural way both the impressive isotropy of the burst distribution as well as the roll-over of the brightness distribution for low fluxes which leads to $V/V_{\max} \approx 0.3$ instead of 0.5 expected for a homogeneous distribution in Euclidean space (Meegan at al. 1993).

Within this frame, the most popular family of models are models based on sudden merger of two neutron stars or a neutron star and a black hole (Paczynski 1991). Such a merger is claimed to lead to ejection of a fraction of the disrupted star at ultra-relativistic speeds corresponding to the bulk Lorentz factor, $\Gamma > 100$ (Meszaros & Rees 1993). The ejecta are usually considered to be quasi-spherical or mildly collimated into direction of the angular momentum vector of the system. We consider below the implication of the detected proper motion of the optical point source to this general scenario.

Identifying the proper motion of the optical source as a motion of relativistic ejecta observed at very small angle to the ejecta axis, we obtain that the opening angle of the ejecta must be, at most, of the order of the Doppler beam ($\ll 1/\Gamma$) (otherwise, one would see on the sky the expanding source, rather than the propagating source). Let us assume that the distance to the GRB 970228 is equal to 1 Gpc which corresponds to a rather moderate cosmological redshift of $\sim 0.16$. It is a very conservative assumption since on the basis of the gamma-ray brightness the source may be possibly placed at $z \approx 0.3$ (Wijers, Rees & Meszaros 1997), provided it is a standard cosmological candle. Even larger distance is suggested by weakness or absence of the host galaxy. Thus, for a distance of 1 Gpc measured by HST the proper motion $540''$ year$^{-1}$ translates into the bulk Lorentz factor $\Gamma \sim 8500$.

For such large Lorentz factor the ejecta travel for a very large distance $r > 10^{23}(\Gamma/10^4)^2$ cm. Thus the ejecta can not avoid interacting with the matter swept over such a journey and the mass of the gas collected is at least $\Delta M \approx 10^4(\Gamma/10^4)^4 M_\odot$. The energetic requirements of equation 1 can be applied to the case of cosmological models as well. In particular when $\Gamma = 10^4$, we find that

$$E > 10^{65}(\Gamma/10^4)^6(\rho/10^{-30}) \text{ erg}. $$  

Such a requirement seems to rule out all of the cosmological models. The variability of the extended source pushes the above requirement up by six orders of magnitude.

5 DISCUSSION AND CONCLUSIONS

The proper motion of the discovered point-like optical counterpart imposes severe constraints on the origin of gamma ray bursts. In the following discussion we make an assumption that the moving point source is directly related to the GRB. The relation of fading extended object to the GRB event seems less clear. Thus we discuss various possibilities, assuming that either it is or it is not directly related to the GRB.

The comparison of the observed proper motion with the parallax expected at a given distance puts a firm limit on the minimum distance to the source equal 6.6 pc. This conclusion rules out all models connecting the gamma burst phenomenon with Oort cloud.
The assumption of cosmological distances to gamma ray bursts leads also to serious problems. Observed proper motion requires huge Doppler factors ($\Gamma \sim 10^4$) for the bulk of the motion of the radiating gas. The time evolution of the accompanying extended source require the Doppler factor even by a factor of 10 higher. We have shown that the energy required to propagate such a highly relativistic gas is eleven orders of magnitude higher than that available in a collision of two neutron stars.

Also the models locating gamma ray bursts in the Galactic halo may have difficulties. The energetic requirements can be satisfied if the typical distance to a GRB is less than 100 kpc. Such a distance scale is marginally consistent with the BATSE observations of isotropy of the GRB distribution. The delayed turn-on models (DT) require that the sources burst $4t^2 \approx 16$ more times, while in the beaming model (BM) no such requirement arises.

The $\Gamma$ factors required by the variability of the extended source make the energetic requirements prohibitive for the galactic halo models of GRBs.

The apparent motion of the point source or the variability of the extended source do not constrain the models for distances in the nonrelativistic region $A$, i.e $6.6 \text{ pc} < D < 10 \text{ kpc}$. For example we cannot rule out the moderately local origin of the gamma bursts. If the bursts come from the distances of order of 5–100 pc and the roll-over of the brightness distribution is an apparent effect caused by the detection threshold, like suggested by Bisnovatyi-Kogan (1996), who argues that such a geometrical distribution may also be acceptable at the present stage.

All these conclusions are based on assumptions that (i) the identification of the optical counterpart of the gamma ray burst was correct and (ii) the measurement of the proper motion of the point-like optical counterpart was undoubted. Unfortunately, further observations of GRB 970228 are difficult since the source approaches the Sun on the sky. This part of the sky will be visible again in a few months but the source is rapidly fading at all frequencies so its future detection may be impossible.

Therefore the confirmation of our conclusions would rather come from the detection of similar behavior of the optical counterparts of other gamma bursts well localized by Beppo/SAX. Since several such bursts a year are expected at least one or two should be bright enough to allow the accurate measurements and similar analysis.

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