Astron. Astrophys. 329, 61–67 (1998)

ASTRONOMY AND ASTROPHYSICS

A search for prompt radio emission of gamma-ray bursts

Arnold O. Benz and Gunnar Paesold

Institute of Astronomy, ETH-Zentrum, CH-8092 Zürich, Switzerland

Received 11 June 1997 / Accepted 12 August 1997

Abstract. A conducting fireball expanding at relativistic speed into an ambient magnetic field generates a rapidly changing electric current which emits coherent electromagnetic radiation at radio frequencies. The critical frequency (upper limit of the emission) strongly depends on the Lorentz factor of the expansion. We have searched for simultaneous radio emission in the data of solar radio spectrographs at times when BATSE reported a non-solar gamma-ray burst (GRB) within the beams of the radio telescopes. Solar spectrographs are less sensitive than single frequency receivers, but yield a broad overview on the spectrum ideal for discriminating against atmospheric and man-made interference. In 7 well-observed cases no radio emission was found. This puts upper and lower limits on the Lorentz factor of the fireball expansion in GRBs if the source distance is less than 1 kpc, i.e. if GRBs are local. The coherent expansion radiation is not observable with current instruments if the GRB sources are at $\geq$ 1 kpc.

Key words: gamma rays: bursts – radio continuum: general – black hole physics

1. Introduction

It has been suggested that a possible signature of an exploding fireball is a burst of *coherent* radio emission (Rees 1977). A conducting plasma expanding into an ambient magnetic field generates a time variable surface current. In a rapid expansion an electromagnetic pulse is generated that propagates as a packet of radio waves at frequencies exceeding the plasma frequency. The emission mechanism operates efficiently for short expansion time, and its limiting radiation field is the *pushed-up* interstellar magnetic field. Rees (1977) has suggested that a radio burst may be associated with a hypothetical primordial black hole (PBH) explosion. Expanding fireball models have also been proposed for gamma-ray bursts (GRB): GRBs are likely to be highly super-Eddington events. Therefore, hot plasma expanding at ultra-relativistic velocities is an element of most GRB models. The coherent radio emission is practically simultaneous with the GRB except for the reduced propagation speed of the radio waves by interstellar dispersion. A maximum delay of a few seconds has been predicted by Palmer (1993) for galactic GRBs.

Another coherent radio emission is well known from atomic bomb explosions (Karzas & Latter 1965: Vittitoe 1970), where up to 1% of the initial energy first appears in the form of gamma-rays. They produce a cloud of Compton electrons propagating into the ambient magnetic field and radiating coherent synchrotron emission for roughly one gyroperiod. Since the radiation field of this emission process cannot exceed the *ambient* magnetic field, it is undetectable at cosmic distances (Katz 1994).

A third radio emission, *incoherent* synchrotron radiation of shockwave produced electrons, has been proposed by Paczyński & Rhoads (1993), who estimated the radio emission from GRBs. They find that the synchrotron emission increases as the fireball surface expands. The peak flux is of the order of ten μJy for GBRs at a distance of 1 kpc, but much less if the source is optically thick (Katz 1993). The peak of synchrotron radiation may be delayed by several minutes relative to the gamma-ray burst for galactic GRB models. The predicted time delay is thus different for coherent and incoherent emissions. More important, a coherent mechanism may be much more efficient than the incoherent process.

Previous searches for radio emission of GRBs include many sensitive observations *delayed* by hours or days (e.g. Schaefer et al. 1989, 1994; Koranyi et al. 1994, 1995; Frail et al. 1994, and references in McNamara, Harrison & Williams 1995) and a few less sensitive *simultaneous* radio observations by dedicated telescopes surveying a large fraction of the sky for prompt emissions (Baird et al. 1975; Inzani et al. 1982; Dessenne et al. 1996). The previous searches for prompt radio emission of GRBs have all been accomplished by single frequency recordings at 151 MHz (complemented at 408 MHz by Inzani et al.). Baird et al. have not found any associated radio emission above 10^5Jy. However, Inzani et al. reported radio emission stronger than 10^5Jy and above the 89% confidence level for association in 20% of all cases. Dessenne et al. have observed no simulta-

Send offprint requests to: A.O. Benz

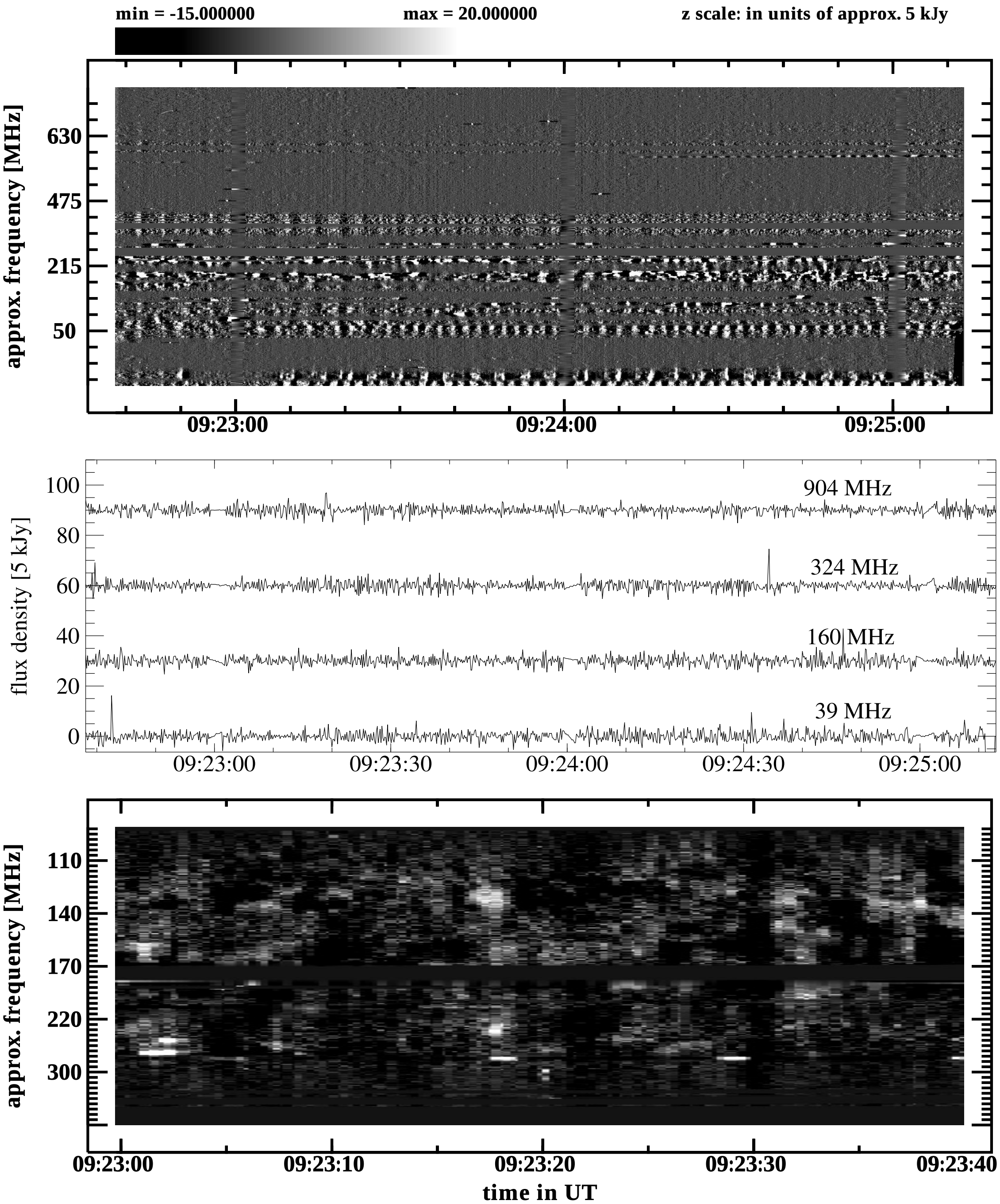

Fig. 1. During the gamma-ray burst of 1992/11/02, starting at 09:23:17 UT with a duration of 5.4 s, the Tremsdorf and Weissenau spectrographs have observed within a beamwidth of the source position. The radio data is presented in two forms: *Top:* Spectrogram of the total frequency range observed in Weissenau, showing enhanced radio emission (bright) in the total frequency range. *Middle:* For some arbitrary channels of the same data the flux density is plotted vs. time. The rms noise is estimated to be of the order of 10^4Jy. *Bottom:* An enlargement of the Tremsdorf data is presented showing solar type I bursts and terrestrial interference.

neous emission in one case of simultaneous observation with a sensitivity (3σ) of 73 Jy.

The possible detections of Inzani et al. (1982) definitely need confirmation as chance coincidences with man-made, solar or atmospheric interference cannot be excluded. Such interference as well as cosmic pulses have their characteristic signatures in spectrograms and can easily be distinguished by spectrometers (cf. Fig. 1).

We compare the (negative) result of this search with the predictions of fireball models. A rapidly expanding conducting sphere will be assumed, e.g. an exploding pair-plasma as expected from gamma-gamma interactions in intense gamma-ray sources. The coherent radio emission is calculated for high

Lorentz factors as estimated for GRB models assuming an exploding primordial black hole (PBH). PBHs exploding in the present era have masses $\leq 10^{14}$g, and about 50% of the rest mass energy may be transformed into electron-positron pairs of energy $\approx 100 \left(\frac{m}{10^{14}\mathrm{g}}\right)^{-1}$ MeV (e.g. Blandford 1977). Such an interpretation of GRBs was put forward already by Page & Hawking (1976, cf. also review by Halzen et al. 1991) and more recently for very short events by Cline & Hong (1992, 1996). It is, however, not a necessary assumption for the evaluation of these radio observations.

2. Observations

The radio telescopes involved in this search observed a broad region centered at the Sun. We have selected all non-solar GRBs that have been observed by BATSE onboard CGRO until 1997/08/03 (Third BATSE Catalog, Meegan et al. 1996, and updated version by the Compton Science Center) to have occurred within 10 degrees of the position of the Sun (in both declination and right ascension). The BATSE instrument measures the hard X-ray and gamma-ray spectrum with eight uncollimated, shielded NaI scintillation counters each sensitive in the energy range 25 keV - 1.9 MeV (Fishman et al. 1989, 1992). The collecting area of each detector is 2025 cm^2. The threshold fluence (>20 keV) for detection depends on the background counts and burst duration. It is typically 10^{-7}erg cm^{-2}. From the different count rate of the detectors the source position can be determined within a few degrees depending on the total counts of the event. Solar and non-solar events can be distinguished both from the position and from the spectrum, where non-solar bursts appear harder. The rate of erroneous classifications is believed to be small (Schwartz et al. 1992).

We have searched for radio emissions in the data of three similar radio spectrographs located in Bleien (Daedalus, Perrenoud 1982), Tremsdorf (Mann et al. 1992) and Weissenau (Urbarz 1969). The three spectrographs had similar properties: They observed in the range from about 40 to 1000 MHz with a sweeping receiver fed by a parabolic antenna of about 7 m diameter, and they registered on film. The sensitivity was similar in the three instruments since the noise is dominated by the background radiation of the Sun, and the spectrometers swept through the spectrum with about 1 MHz resolution (at 300 MHz) and 4 times per second. The film recording, in practice, further reduces the sensitivity. This can be considerably improved if the film is digitized. The final sensitivity is of the order of 10^5Jy.

The full width at half power of the beam is

$$\theta_{FWHP} \approx 10.5\ \lambda_m \left(\frac{7\mathrm{m}}{d}\right) \quad [\mathrm{deg}]\ , \tag{1}$$

where λ_m is the wavelength in meters and d is the diameter of the parabola.

Fig. 1 displays examples of radio spectrograms. The original film records have been digitized so that a frequency-variable background can be subtracted and weak signals become visible. Horizontal lines are caused by terrestrial transmitters and are obvious in Fig. 1a, in particular between 50 and 450 MHz. Narrowband blobs of less than one second duration in Fig. 1c can be attributed to a solar noise storm producing type I bursts. An example thereof is the event at 09:23:18 UT on 240 MHz having a flux density of $2.1 \cdot 10^5$ Jy. Broadband peaks and drifting features would be easily recognizable in the spectrograms. An event at 09:23:20 UT visible in Fig. 1c at 280 - 300 MHz, however, is not accepted since it does not continue to low frequencies and does not drift. Furthermore, it does not show in the Weissenau picture (Fig. 1a). Fig. 1b displays the data of some selected frequency channels of the spectrogram in Fig. 1a. It gives an impression of the noise. The flux calibration is approximated making use of the radiometer equation.

Interstellar dispersion would delay the radio signal of an expanding fireball relative to the vacuum by

$$\delta t = 1.345 \cdot 10^{-3} \nu^{-2} \int n_e ds \ \ [\mathrm{s}]\ , \tag{2}$$

where n_e is the electron density (in cm^{-3}) along the path element ds (in cm) and ν is the observed frequency (in Hz). Eq. (2) indicates that low-frequency emissions are more delayed. Let for example be $n_e = 0.01$ cm^{-3} and the distance 100 pc. Eq. (2) then predicts the delays of the signals at 300 MHz and 100 MHz to be different by 0.36 s. Thus, the broadband emission of a galactic radio pulse would be a drifting structure in a spectrogram (like a pulsar signal) having a well-defined form given by Eq. (2):

$$\dot{\nu} = -372\nu^3 \frac{1}{\int n_e ds} \ \ [\mathrm{Hz/s}]\ . \tag{3}$$

For the current instruments the distance must exceed about 25 pc for the drift to be noticeable. It makes the signal distinguishable from atmospherics (no measurable drift) and solar radio bursts having different drift characteristics (most similar are type III bursts with $\dot{\nu} \sim -\nu^{1.8}$).

If the emission is shorter than the sweep time at a given frequency, the signal would appear as a string of drifting dots. The instantaneous apparent bandwidth is

$$\delta\nu = \dot{\nu}\tau_r \ \ , \tag{4}$$

where $\dot{\nu}$ is the apparent drift rate as given by Eq. (3) and τ_r is the pulse duration at the given frequency.

The radio spectrometers sweep through the spectrum. If the sweep direction is opposite to the drift caused by interstellar dispersion, the signal strength is reduced. For drift rates of the dispersed emission smaller than the sweep rate, the apparent bandwidth becomes appreciably narrower than the instantaneous bandpass $\Delta\nu$ of the instrument, and the measured signal strength is reduced by $\delta\nu/\Delta\nu$. The minimum distance for which this effect becomes relevant is 100 pc in the case of the

Bleien instrument and more than 300 pc for the others (assuming n_e = 0.01 cm^{-3}). Since the effect on the observed flux density is small up to about 1000 pc, it is neglected in the following.

The expansion time τ will be derived later (Eq. 6). The shortening of the ray path reduces the duration of the radio pulse by γ^2, thus $\tau_r = \tau/\gamma^2$. For any reasonable observing bandwidth, the apparent pulse duration, τ_a, at a given frequency is therefore determined by dispersion: $\tau_a = \Delta\nu/\dot{\nu}$.

Simultaneous radio coverage of a GRBs observed by BATSE was found in 7 cases. They are listed in Table 1. Date and time refer to the BATSE trigger as given by Meegan et al. (1996). The duration is defined by the interval between 5% and 95% of the total counts. The fluence is the total energy received per unit area integrated over the event and the spectrum > 20 keV. The duration and fluence could not be measured in all cases due to data gaps. The comments indicate the observing radio station (B for Bleien, T for Tremsdorf and W for Weissenau) and some prevailing forms of interference, such as a solar noise storm and terrestrial 'atmospherics' caused by lightning.

3. Interpretation

A spherical conductor expanding into a previously uniform magnetic field, B_0, produces a toroidal surface current. The strength of this current is proportional to sinθ, where θ is the angle between the normal to the conducting surface and $\boldsymbol{B_0}$. As the expansion proceeds, the current varies and produces magnetic dipole radiation. Adopting an earlier calculation by Colgate & Noerdlinger (1971), Blandford (1977) has derived the radiated energy for an ultrarelativistic adiabatic expansion, where the total (kinetic plus radiated) energy, E, is conserved per solid angle. For such an explosion, Blandford has derived the time dependent Lorentz factor of the expanding surface

$$\gamma = \frac{\gamma_0}{1+(t/\tau)^3} \quad , \tag{5}$$

where γ_0 is the initial Lorentz factor of the expansion and τ is a deceleration time defined as

$$\tau = \left[\frac{3E}{2c^3\gamma_0^2 B_0^2 sin^2\theta}\right]^{\frac{1}{3}} \quad . \tag{6}$$

In Eqs. (5) and (6) the expansion is assumed into a vacuum; the decelerating effect of the ambient gas is neglected. Note that τ and $\gamma(t)$ depend also on θ. The spectral energy per sterad of the radiation field then becomes

$$\mathscr{T} = \frac{c^3 B_0^2 sin^2\theta}{4\pi^2}\tau^4 \left|F\left(\frac{\omega}{\omega_c}\right)\right|^2 \quad \text{[erg/Hz ster]}, \tag{7}$$

where

$$F(\xi) = \int_0^\infty dx\ x\ exp\left[i\xi\left(x+\frac{x^4}{2}+\frac{x^7}{7}\right)\right] \quad . \tag{8}$$

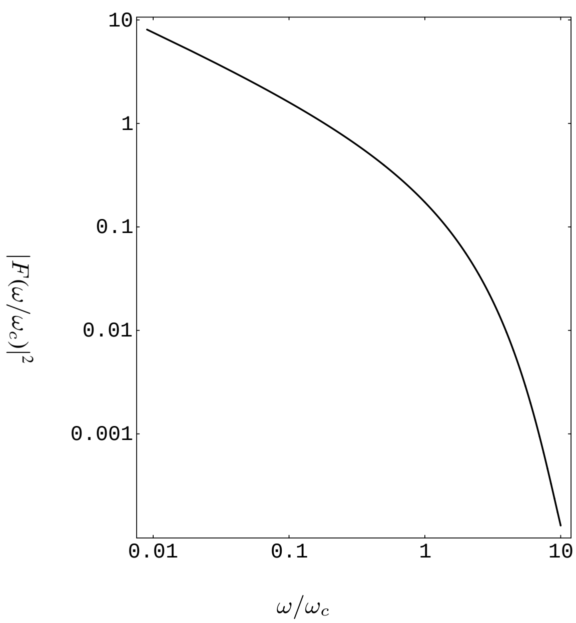

Fig. 2. Radio spectrum of an exploding conducting sphere caused by coherent expansion radiation according to Eqs. (7) and (8). The frequency unit is the critical frequency ω_c, defined in Eq. (9).

The spectrum of an electromagnetic pulse according to Eqs. (7) and (8) is plotted in Fig. 2. It is relatively steep at frequencies above the critical frequency defined by

$$\omega_c = \frac{2\gamma_0^2}{\tau} \quad . \tag{9}$$

The critical frequency is the approximate location of a break in the spectrum. The spectral index for $\nu \ll \nu_c$ is 0.57; for $\nu \gg \nu_c$ it is 4. The critical frequency can be evaluated from Eqs. (6) and (9),

$$\nu_c = 1800 \cdot \gamma_6^{8/3} b^{2/3} E_{31}^{-1/3} \quad \text{[GHz]}, \tag{10}$$

where we have defined

$$E_{31} = \frac{E}{10^{31}\text{erg}} \tag{11}$$

$$\gamma_6 = \frac{\gamma_0}{10^6} \tag{12}$$

$$b = \frac{B_0 \sin\theta}{10^{-5}\text{Gauss}} \quad . \tag{13}$$

As will be shown below, the value of $E = 10^{31}$erg is in the range of kinetic energies suggested for exploding PBHs in the present era.

4. Results and discussion

No broadband meter wavelength radio emission has been observed simultaneously and within 2 minutes of a GRB observed by BATSE. The upper limit is a radio flux density of roughly 10^5Jy. We discuss two possible reasons for the non-detection of coherent emission produced by the expanding fireball:

Table 1. Date, time, duration (between 5% and 95% of the total number of counts), fluence > 20 keV of gamma-ray bursts, and their angular distance to the Sun observed simultaneously by BATSE and solar radio spectrometers.

date yy/mm/dd	time UT	duration [s]	fluence [erg cm^{-2}]	angle to Sun [deg]	comments
92/02/29	15:04:08	12.2	1.2E-6	6.6	B, W
92/07/24	17:09:10	45	1.3E-6	7.2	W, atmospherics
92/11/02	09:23:17	5.4	5.9E-6	5.8	W, T, noise storm
93/04/15	09:19:48	54.3	3.0E-6	12.4	T
93/09/10	07:39:39	40	-	6.1	T
93/09/10	08:04:02	0.5	0.2E-6	10.4	T
94/03/14	09:59:49	70.3	3.9E-6	4.3	T

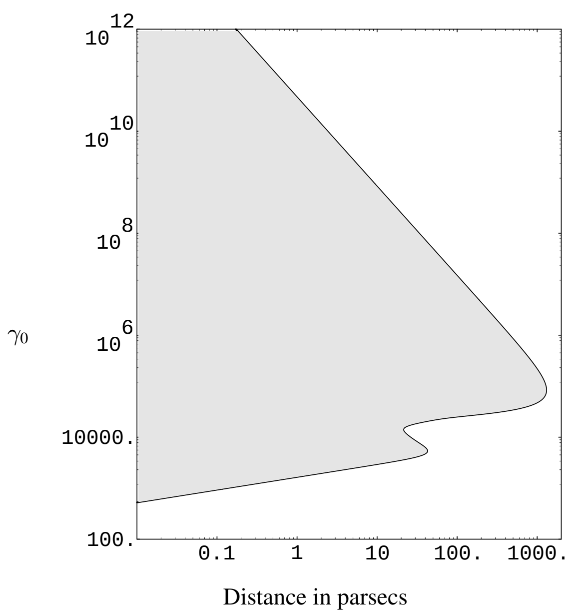

Fig. 3. The region of sensitivity of the radio spectrographs for the detection of radio emission of GRB associated fireballs is shaded. The initial Lorentz factor of the fireball expansion, γ_0, and the distance in parsecs for an observing frequency of 300 MHz are the free parameters, an energy of 10^{31} erg has been assumed.

- The critical frequency, ν_c, of GRB may be below the range of the spectrographs (100 MHz for Bleien and Tremsdorf, 40 MHz for Weissenau). Eq. (10) indicates that ν_c depends strongly on the initial Lorentz factor: $\nu_c \propto \gamma_0^{8/3}$. It also depends on the ambient magnetic field and, to a third root, on the initial kinetic energy of the fireball. If the critical frequency is below the observing frequency, the flux density is strongly reduced (cf. Fig. 2).
- The critical frequency may be above the observed frequency range, but the source is too weak or at a large distance.

For a given energy and initial Lorentz factor, Eq. (6) yields the expansion time. From the spectral energy (Eq. 7) divided by the pulse duration τ_r, the radio flux density at a given distance can be evaluated. Reduced for finite observing bandwidth, the flux density was compared to the sensitivity of the spectrometers. Fig. 3 shows the observational range of the solar radio spectrographs for a 10^{31}erg explosion in dependence of the initial Lorentz factor γ_0 and the distance in parsecs for a threshold sensitivity of $\approx 10^{-18} \frac{\mathrm{erg}}{\mathrm{Hz\ s\ cm^2}} = 10^5$Jy. The shaded area represents the region which is covered by this survey. Fig. 3 shows that the most favorable conditions for the detection of galactic fireball explosions are

$$10^5 \leq \gamma_0 \leq 10^7 \quad . \tag{14}$$

If the fireball is caused by an exploding PBH, the initial kinetic energy is related to γ_0 through $\gamma_0 \approx 8.8 \cdot 10^5 E_{31}^{-1}$.

The possibility that GRBs are produced by exploding PBHs has been suggested by Page & Hawking (1976), more recently by Cline & Hong (1992) and others. Appropriate model-dependent calculations generally suggest short duration events of relatively low gamma-ray luminosity. Such GRB sources would therefore have to be nearby. There are two extreme models for the spectra of a PBH explosion (Page & Hawking 1976): For a very soft hadronic spectrum the time duration of the gamma-ray burst of a $\approx 7 \cdot 10^{13}$g PBH is of the order of 10^{-7}s and for a hard (QCD-like) spectrum, the time duration for the burst of a 10^{10}g PBH is about one second.

A bimodal distibution of the GRB duration has been reported by Kouveliotou et al. (1993). The two populations separate at about 2 s. We will consider GRBs with duration < 2 s as possible PBH candidates. For the latter type of models the source distance is limited by the threshold sensitivity of the X-ray detector. Assuming that 10% of a maximum mass of 10^{14}g is converted into > 20 keV photons, BATSE is sensitive to a source distance of 27 pc.

Under the assumption that the 197 BATSE events shorter than 2 s which have occurred during the effective observing time of 1.32 y of the Third BATSE Catalog (Meegan et al. 1996) were due to PBH explosions with properties that prevent an observation by radio spectrographs, i.e. with parameters of the PBH outside the shaded region in Fig. 3, the rate of evaporating PBHs is

$$\frac{dn}{dt} \approx 1.8 \cdot 10^{-3} \quad [\mathrm{pc}^{-3}\ \mathrm{y}^{-1}] \ . \tag{15}$$

The value in Eq. (15) is well above the upper limit of the PBH decay rate, $2.2 \cdot 10^{-5}$ pc^{-3}y^{-1}, derived in Cline & Hong (1992) from the observed X-ray background, suggesting that not all of these GRBs can be PBH explosions or that a different model for the gamma-ray emission of PBH must be used.

At least one of the GRBs observed simultaneously (cf. Table 1) was of the one-second type and thus a more likely candidate for an exploding PBH. In the following we discuss non-detections of metric radio waves under the assumption of the PBH model of GBRs. Fig. 3 demonstrates that fireballs of 10^{31} erg should be observable by the radio spectrographs up to a distance of about 1 kpc. Taking into account that the observation depth of BATSE is only 27 pc, the radio non-detections give observational bounds for the initial Lorentz-factor γ_0,

$$\gamma_0 \leq 1.5 \cdot 10^4 \tag{16}$$
$$\gamma_0 \geq 1.7 \cdot 10^8 \quad . \tag{17}$$

This means that either the initial Lorentz factor is lower then expected, what could mean that the explosion scenario is more of an extreme Hagedorn type ($\gamma_0 \approx 300$), or it is higher (Eq. 17) what does not seem reasonable to us.

Another interpretation could be that the observed GRBs were not exploding PBHs. Then an upper limit on the occurrence of PBH explosions can be derived from the selected volume of observations and the effective observing time (0.53 years). Assuming that the PBHs are uniformly distributed, the rate of explosions is

$$\frac{dn}{dt} \leq 4.8 \cdot 10^{-3} \quad [\mathrm{pc}^{-3}\ \mathrm{y}^{-1}] \, . \tag{18}$$

For Eq. (18) a confidence level of 90% was chosen and it has been assumed that the number of explosions per year is Poisson distributed.

Without the assumption of the PBH model for GRBs, thus with an open relation between energy and expansion velocity, the absence of radio emission during GRB also puts limits on γ_0, E, and the distance D of the sources. Eq. (7) suggests that the observed flux density scales as $E^{-2/3}$ for very large energies where $\nu \gg \nu_c$. Therefore, extragalactic GBR sources requiring such energies cannot be detected by the radio spectrographs.

5. Conclusions

We found no simultaneous radio emission associated with 7 non-solar gamma-ray bursts detected by BATSE, although any highly relativistic fireball expanding into an ambient magnetic field should produce a detectable expansion radiation under the assumption that it is conducting. Two possible interpretations have been presented: (i) The initial Lorentz factor of the expansion is lower than about $1.5 \cdot 10^4$, or (ii) the distance to the observed GRB sources is more than 1 kpc.

The instrumental sensitivity may be improved by two orders of magnitude through a dedicated instrument. However, if GRB sources are at large distance, they involve much energy, thus a long deceleration time and low critical frequency. The coherent expansion radiation considered here then becomes much weaker at decimetric wavelengths and the emission remains unobservable for a GRB distance $\geq$ 10 kpc.

Assuming that the gamma-ray bursts are due to PBH constrains the initial Lorentz-factor γ_0, and new bounds on the distribution of PBH in our local neighborhood can be derived. Our observations included only one event with duration $<$ 2s. Therefore, we consider them as not suitable for firm conclusion on PBH models for GRBs. Nevertheless it is remarkable that solar radio astronomers never have reported non-solar drifting events showing interstellar dispersion in the past 50 years. Since they may have slipped the attention of the data evaluation, the observers are strongly advised to search for events with drifts of the shape $\dot{\nu} \sim -\nu^3$ as given by Eq. (3).

Note that the observations in radio waves survey a much larger volume for PBH explosions than in X-rays and gamma-rays. Any explosion having $1.5 \cdot 10^4 \leq \gamma_0 \leq 1.7 \cdot 10^8$ at less than 27 pc, the sensitivity limit of BATSE, must be clearly visible in solar radio spectrograms. The probability for detection even increases at larger distances up to about 1 kpc due to the spectral drift caused by interstellar dispersion. A systematic search for such events with current radio instruments would cover a volume three orders of magnitude larger than for X-ray observations.

Acknowledgements. H. Aurass (Astrophysical Institute Potsdam) and the late H.W. Urbarz (Weissenau Observatory) have kindly provided important spectral data at metric wavelengths. The spectral observations have been carried out with the help of many persons of the observing groups. The authors gratefully acknowledge the effort of the BATSE Operations Team and the Compton Science Center Support Center in processing the 3B catalog data. We thank in particular K. Appert, J.I. Katz and D.M. Palmer for helpful discussions. The operation of the spectrometer Daedalus was financially supported by the Swiss National Science Foundation (grant No. 20-46656.96 and older).

References

Baird G.A. et al., 1975, ApJ 196, L11
Blandford, R. D., 1977, MNRAS 181, 489
Cline D.B., Hong W., 1992, ApJ 401, L57
Cline D.B., Hong W., 1996, Astropart. Phys. 5, 175
Colgate S.A., Noerdlinger P.D., 1971, ApJ 165, 509
Dessenne C.A.-C. et al., 1996, MNRAS 281, 977
Fishman G.J. et al., 1989, The Burst and Transient Source Experiment (BATSE) - Scientific Objectives and Capabilities, GRO Science Workshop (Greenbelt: GSFC), 3

Fishman G.J., Meegan C.A., Wilson R.B., Pacieses W.S., Pendleton G.N., 1992, in The Compton Observatory Science Workshop (NASA CP 3137), 26
Frail D.A. et al., 1994, ApJ 437, L43
Halzen F., Zas E., MacGibbon J.H., Weeks T.C., 1991, Nature 353, 807
Inzani P., Sironi G., Mandolesi N., Morigi G., 1982, in Lingenfelter R.E., Hudson H.S., Worall D.M., eds, AIP Conf. Proc. Vol. 77, Gamma-Ray Transients and Related Astrophysical Phenomena, p.79
Karzas W.J., Latter R. Phys. Rev., 1965, 137, B1369
Katz J.I., 1993, in AIP Conf. Proc. 307, Gamma-Ray Burst (eds. G.J. Fishman, J.J. Brainerd, K. Hurley), 529
Katz J.I., 1994, ApJ 422, 248
Koranyi D.M., Green D.A., Warner P.J., Waldram E.M., Palmer D.M., 1994, MNRAS 271, 51
Koranyi D.M., Green D.A., Warner P.J., Waldram E.M., Palmer D.M., 1995, MNRAS 276, L13
Kouveliotou, C. et al., 1993, ApJ 413, L101
Mann G., Aurass H., Voigt W., Paschke J., 1992 ESA Journal SP-348, 129
McNamara B.J., Harrison T.E., Williams C.L., 1995, ApJ 452, L25
Meegan C.A. et al., 1996, ApJS 106, 65 (3B catalog)
Page D. N. Hawking S. W., 1976, ApJ 206, 1
Palmer D.M., 1993, ApJ 417, L25
Paczyński B., Rhoads J., 1993, ApJ 418, L5
Perrenoud M., 1982, Solar Phys. 81, 197
Rees, M. J., 1977, Nature 266, 333
Schaefer B.E., 1989, ApJ 340, 455
Schaefer B.E. et al., 1994, ApJ 422, L71
Schwartz R.A., Dennis B.R., Fishman G.J., Meegan C.A., Wilson R.B., Pacieses W.S., 1992, in The Compton Observatory Science Workshop (NASA CP 3137), 457
Urbarz H., 1969, Solar Phys. 7, 147
Vittitoe C.N., 1970, Sandia Laboratories, SC-DC-70-4900

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.