Nonthermal Optical Transients from Relativistic Fireballs

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A general upper bound is derived on the total energy in incoherent nonthermal transients at frequency ν from relativistic fireballs with bulk Lorentz factors Γ and observed duration Δt, and shown to be about $10^{-2}[\Gamma\nu\Delta t]^3$ ergs. It is suggested that detection in the optical can be achieved with the next generation of ground based gamma ray telescopes and/or small optical telescopes. Phenomena within the Galaxy such as accretion disk flares and neutron star magnetospheric discharges might be discovered in this way.

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It used to be thought that the Eddington limit placed an upper limit on the rate of radiation that could be emitted from a compact astrophysical object. Gamma ray bursts (GRB's) at cosmological distances show that this cannot be the case. Their isotropic equivalent luminosities are typically 10^{51} erg s^{-1}, sometimes even more, and, even if their beam fills only 10^{-4} of the sky, their luminosities are super-Eddington by many orders of magnitude. Moreover, their apparent ultrarelativistic terminal Lorentz factors, $\Gamma \geq 100$, show a remarkable dearth of baryons. But surely they are fueled by the gravitational energy of baryons. How they accomplish such super-Eddington luminosities without dragging out a baryonic wind is still an open question. It may be that the bursters are strange neutron stars that restrain baryonic outflow by quantum chromodynamics forces, or it may be that the baryon-pure jets connect to black holes and are fed either by neutrino annihilation on the horizon-threading field lines, or by electromagnetic energy extraction from the black hole. Observational diagnostics to distinguish between the various possibilities are desired. Small scale time structure is hard to detect in gamma rays, however, and lower energy photons, until recently, were known to be produced only in the afterglow stages of the burst, when information about the central powerhouse of the burster is probably lost. However, there is now at least one burst where a prompt optical flash [1–3] was detected [4]—GRB 990123. Although this GRB was an extremely bright one, it stands to reason that most GRB's are accompanied by similar, weaker flashes that usually escape detectors such as ROTSE [4]. Here we investigate the possibility that optical flashes, though usually too weak to be caught until now, may be common to GRB's and possibly to "microbursts" within our Galaxy. If detected, they could provide information about (a) the dimensions of the burster and (b) the bulk Lorentz factors. Conceivably, the data might eventually become revealing enough to distinguish between black holes and neutron stars. The question, in any case of interest to observers of optical transients, is how the maximum energy in an optical flash scales with observed duration $\triangle t$.

A classical transient thermal source of optical radiation of observed duration $\triangle t$ and temperature T would be limited to a total energy output E as given by

$$E \sim c^2(\triangle t)^3\sigma_{SB}T^4 \sim \left(\frac{\triangle t}{1s}\right)^3\left[\frac{T}{10^4\ \mathrm{K}}\right]^4 \times 10^{33}\ \mathrm{erg}\,, \tag{1}$$

where T is the characteristic surface temperature and σ_{SB} denotes the Stefan-Boltzmann constant. Transient thermal sources would put out much less than a solar luminosity if $\triangle t \ll 1$ s (unless $T \gg 10^4$ K), and, at a typical intragalactic distance of 1 kpc, would have apparent magnitudes much greater than 20. They could not stand out above the night sky background even for their short duration. A much larger temperature than 10^4 K, moreover, would imply a low efficiency for optical emission. This limit applies to static or nonrelativistically expanding sources.

For incoherent nonthermal sources such as expanding fireballs, however, the temperature of the optically emitting electrons can be much larger. The brightness temperature T'_B in the fluid frame is limited only by the requirement that there is no inverse Compton catastrophe [5,6]

$$\begin{aligned} T'_B &\leq (10^{12}\ \mathrm{K})B_1'^{(-1/7)} \\ &\approx (10^{12}\ \mathrm{K})\left[\frac{U'}{(0.025\ \mathrm{erg\,cm^{-3}})}\right]^{-1/14}, \end{aligned} \tag{2}$$

where B'_1 (U') is the magnetic field strength (energy density) in the fireball frame in cgs units, so the thermal limit expressed by Eq. (1) is greatly relaxed. (Although the brightness temperature limit is usually applied to incoherent synchrotron emission it also applies to inverse Compton emission. In the latter case, B refers to the root mean square field strength of the radiation field.) In addition, the brightness temperature of the photons seen by the observer in the optical must obey $T'_B(\nu_{\rm opt}) < \gamma_{\rm opt}m_ec^2$, where $\gamma_{\rm opt}$

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is the Lorentz factor in the fireball frame of the optically emitting electrons.

If the source is expanding relativistically with the bulk Lorentz factor Γ ($\Gamma \gg 1$), a "relativistic fireball," the limit is relaxed even further as follows: the area of the emitting surface, rather than being $(c\triangle t)^2$, is now limited by the more general expression

$$A < (c\triangle t)^2 \Gamma^4, \tag{3}$$

where $\triangle t$, the observed time duration of the burst, is compressed relative to the expansion time $t_{\rm ex}$ by Γ^2 due to transit time effects.

In the case where the observations are at a given frequency ν that is well below the Wien peak, the limit on energy density in radiation that emerges at frequency of order ν is now less than the blackbody total and is, rather, given by

$$U' \sim 8\pi kT' \frac{\nu'^3}{c^3} = 8\pi kT'(\nu) \frac{\nu^3}{\Gamma^3 c^3}, \tag{4}$$

and the isotropic equivalent total energy emitted by the burst at frequency ν is given by

$$L = U[4\pi R^2]c < \Gamma^2 U' 4\pi [c t_{\rm ex}]^2 c \sim \Gamma^2 U' [4\pi c \triangle t \Gamma^2]^2 c \sim 32\pi^2 kT'(\nu')(\nu\Gamma)^3 \triangle t^2, \tag{5}$$

where U is the fireball density in the observer frame, U' is the fireball density in the fireball frame (all quantities with primes refer to the fireball frame), ν is the frequency of the radiation as seen by the observer, $T'(\nu)$ is the brightness temperature in the fireball frame, $t_{\rm ex}$ is the expansion time in the observer frame, and L is the isotropic equivalent luminosity for the observed duration $\triangle t$.

Finally, the total isotropic equivalent energy in the pulse is limited by

$$E = L\triangle t = 32\pi^2 [kT][\Gamma\nu\triangle t]^3 \lessapprox 0.04 B'^{(-1/7)} [\Gamma\nu\triangle t]^3 \text{ erg}. \tag{6}$$

Note that, at a given upper bound on E, Γ depends on the energy density to the power (1/42), and a useful limit can be obtained without a fundamental analysis of the energy density. The latter is likely to be between 10^{-10} and 10^{33} erg cm^{-3}, whereas Γ^3 is rather uncertain.

There are several other constraints.

(i) There must be enough time to accelerate the high energy electrons to the energy of about kT_B. Assuming the acceleration time is longer than the gyroperiod, $\frac{2\pi}{\omega_c}$,

$$\omega_c \left(\frac{t_{\rm ex}}{\Gamma}\right) > 2\pi. \tag{7}$$

In general this is satisfied for cases that will be of interest to us by a large margin.

(ii) The Lorentz factors of the electron and the magnetic field strength in the frame of the fireball are related to the frequency of observation by

$$\gamma_{\rm opt}^2 \Gamma \frac{eB'}{m_e c} = \nu, \tag{8}$$

where $\gamma_{\rm opt}$ is the Lorentz factor in the fireball frame of the electrons responsible for the optical synchrotron radiation. In the case of inverse Compton, the right-hand side is greater and the arguments below are stronger.

(iii) The efficiency of optical emission is bounded by the fraction of their energy that the emitting electrons can synchrotron radiate over the proper expansion time:

$$\frac{4}{3} \frac{\gamma_{\rm opt} t_{\rm ex}}{\Gamma} U' \sigma c > m_e c^2 \epsilon_{\rm opt}, \tag{9}$$

where $U' = \frac{B'^2}{8\pi}$, σ is the Thomson cross section, and where $\epsilon_{\rm opt}$ is the efficiency with which the electron kinetic energy is converted to optical radiation. This can be shown [using Eq. (8)] to be equivalent to

$$\gamma_{\rm opt}^3 \Gamma < \frac{9}{4} (\nu\triangle t) \left(\frac{\nu r_0}{c}\right) \epsilon_{\rm opt}^{-1} \sim 2 \times 10^7 \left(\frac{\triangle t}{1s}\right) \epsilon_{\rm opt}^{-1}, \tag{10}$$

where r_0 is the classical electron radius and $\nu = 10^{15}$ Hz is assumed.

Finally, by combining Eqs. (6) and (10) with $\gamma_{\rm opt}$, we obtain

$$E \le 10^{62} B_1'^{(-1/7)} (\triangle t/1s)^6 \epsilon_{\rm opt}^{-3} \gamma_{\rm opt}^{-9} \text{ erg} < 10^{62} B_1'^{(-1/7)} (\triangle t/1s)^6 \epsilon_{\rm opt}^{-3} \text{ erg}. \tag{11}$$

Note that for $\gamma_{\rm opt}$ considerably greater than 1, the limit is dramatically lowered and in fact the strong dependence on $\gamma_{\rm opt}$ could translate into a tight upper bound on the latter once E is measured. For γ nearly equivalent to 1, where the maximum allowed E is the largest, the limit on kT_B is stronger by 2 orders of magnitude than that given by Eq. (2), which tacitly assumes a value for $\gamma_{\rm opt}$ of at least 10^2. Thus, to an excellent approximation, the above limit can be strengthened to

$$E \le 10^{60} B_1'^{(-1/7)} (\triangle t/1s)^6 \epsilon_{\rm opt}^{-3} \text{ erg}. \tag{12}$$

The relativistic, nonthermal nature of bright transient optical flashes is exemplified dramatically by optical pulsars and prompt optical afterglow from GRB 990123. A typical optical pulse from the Crab pulsar lasts an order of 1.5 ms, and contains about 10^{33} ergs. Were we to see but a single such pulse and not know that it was from a pulsar, we could deduce that it was nonthermal and/or relativistically expanding simply from the energetics: a thermal surface with a radius of order several light milliseconds and with a plausible surface temperature could not emit as much optical light.

GRB optical flashes.—For the case of the dramatic optical ($\nu = 10^{15}\ s^{-1}$) flash from the recent GRB 990123, from which the isotropic equivalent energy output was nearly $\sim 10^{50}$ erg in less than 30 s, Eq. (6) and plausibility constraints on B'_1 imply that a Γ of at least $\sim 10^{1.5}$ is required, more or less consistent with the bound calculated by Galama *et al.* [7]. This is yet more evidence that high bulk Lorentz factors are attained by GRB fireballs. (Similarly, lower bounds have already been placed on bulk Lorentz factors for outbursts in active galactic nuclei, e.g., [8].)

But there is no way to rule out much higher Γ or smaller time scales. If, for example, the fireball were completely free of baryons, photospheric values of Γ could be as large as the photon-to-pair ratio at the freeze-out radius (which should be smaller than the synchrotron photosphere). The true lower limit on the time scale for significant optical variation can be as small as 10^{-4}–10^{-5} s. Millisecond-scale (or smaller) substructure, often observed in the γ rays, could also appear in the optical for extremely baryon-poor fireballs.

Suppose that Γ were as large as 10^4. Equation (6) then allows a duration nearly as low as 10^{-2} s for the total energy in the optical flash of 10^{50} erg. If we consider a flash that is only 10^{50-n} ergs, then the duration can be as short as $\sim 10^{2-n/3}/\Gamma$ s. Optical flashes from GRB's of less than 1 s duration, weak though they may be, could be numerous and informative. A flash of 10^{45} erg could conceivably be as short as 0.02 s for a Γ of 200. From a luminosity distance of 11 Gpc it would be 17th magnitude.

Microbursters.—A choice of parameters that would satisfy all of the above constraints could be $\Gamma \sim 10^2$, $\gamma_{\rm opt} \lesssim 3$, $B'_1 \sim 10^5$ G, $\nu \sim 10^{15}\ s^{-1}$, $\triangle t \sim 10^{-4}$ s, $L\triangle t \lesssim 10^{34}[\Gamma_2 \nu_{15} \triangle t_{-4}]^3$ erg, where the quantities in brackets are unity in the above illustrative choice. The very small time scale, 10^{-4} s, basically presumes a region of energy release not much more than neutron star dimensions. The emitting surface could be as much as $\Gamma^2 \sim 10^4$ times larger, and the magnetic field near the source could be higher than at the emitting surface by the same factor or more. $\Gamma \gg \gamma_{\rm opt}$ appears necessary for a sufficiently bright optical flash, and this may be significant.

We suggest that optical flashes from relativistic fireballs could be generic to many galactic systems (microbursters) [9]. There are perhaps 100 (pre-BATSE) models for GRB's that could qualify for this category. For example, any perturbation or discharge of a neutron star magnetosphere, even an old weak one, could release a burst of energy that would be baryon poor. Any single optical pulse from an optical pulsar is a good known example. The plasma that emits optical radiation from the Crab pulsar is probably just an outwardly expanding plasma, and many other compact sources could do something similar on a one-time basis. Annihilation of magnetic prominences above accretion disks, for example, could give a similar burst. Although the energy released by the latter would probably excite a wind off the surface of the accretion disk, a baryon-poor fireball might precede the wind. Optical flares of this origin were apparently detected in several low-mass x-ray binaries [10]. These events lasted 1–20 ms and had brightness temperatures exceeding 10^9 K.

Such optical transients may have completely escaped detection until now because, although bright for a brief interval, they would not be sufficiently luminous when time averaged over a typical photographic exposure time to stand out above the noise. For example, it is unlikely that a single optical pulse from the Crab pulsar would have ever been detected had it arrived from an unknown source, yet it should be easily detectable by fast wide field cameras and by upcoming air-Cerenkov telescopes (ACT) such as MAGIC if it is within their field of view [11]. Similarly, any optical source at least as bright as 17th magnitude for at least 0.1 s should be detectable with a 0.5 m optical telescope or with a giant ACT telescope. Catching a burst with a field of view of only a few degrees might take patience, but rapid slewing to long bursts in progress could allow the discovery of optical substructure within the second half (say) of the burst.

A natural ultrashort optical transient would probably have to be at least 10^{-5} s (the Schwarzchild time of a solar mass object) or so in duration, as we associate relativistic fireballs with compact objects of at least a solar mass [12]. But even besides this consideration, constraint (iii) [Eq. (11)] would make much shorter incoherent optical pulses implausible. Substructure in optical pulses on shorter time scales, we predict, should have a power spectrum that obeys Eq. (11).

For weak field ($B \sim 10^8$ G) millisecond pulsars that are at the verge of radio death (rather like Geminga, but remaining at that stage for much longer, with more rotational energy, and hence more numerous), the parameters of an emitting plasma within the light cylinders would be consistent with those chosen above for microbursts. We suggest that old millisecond pulsars might show up in weak optical pulsations even after radio death, and that they could be searched for in the optical.

We note parenthetically that a fundamental limit on incoherent optical flashes confers an unambiguous significance to coherent optical flashes that violate this bound. Thus, for example, an extraterrestrial civilization that outshines its sun with sufficiently brief, well-collimated laser pulses, as our own civilization has very recently become able to do, would be identifiable as such, and optical might thus be the wave band of choice for interstellar communication [13,14].

To summarize, brief optical flashes are theoretically possible at time scales of 10^{-2} to 10^2 s (GRB's), 10^{-5} to 10^{-4} s (Galactic microbursts or baryon-free cosmological GRB's), and submicrosecond (e.g., coherent signals from extraterrestrial intelligence). Large ACT dishes and small telescopes might be the best way to search for these phenomena. If they could measure fine structure in the optical light curve they might distinguish between reverse shock and internal shock models for the energy release.

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