POSSIBLE ASSOCIATION OF ULTRA–HIGH-ENERGY COSMIC-RAY EVENTS WITH STRONG GAMMA-RAY BURSTS

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ABSTRACT

We point out that each of the error boxes of the two highest energy cosmic-ray shower events known overlaps with that of a strong gamma-ray burst (GRB). The GRBs precede the cosmic rays by 5.5 and 11 months, respectively. In one case the strongest known cosmic ray is paired with the strongest gamma-ray burst in the BATSE catalog. The probability of this occurring by chance seems rather small. Without building on post factum statistics, we think the above is remarkable enough to suggest that the cosmic-ray and gamma-ray burst were produced by the same outburst. A time delay, and a small positional disparity, are expected, since the trajectory of a charged cosmic-ray particle is wriggled by intervening magnetic fields. We estimate that the Galaxy's field alone may produce a delay of the order observed. With similar energies going into gamma rays and cosmic rays, we expect only a few times 10% of the strongest GRBs to be followed by a detection of an ultra–high-energy ($E > 10^{20}$ eV) cosmic ray in existing experiments. We discuss some of the implications that follow if such an association is confirmed. For example, the upper limit on the distance of the cosmic-ray source, combined with a much better determined position of the gamma-ray burst source, reduces greatly the volume in which to look for an optical counterpart. The need to produce ultra–high-energy cosmic rays in the GRB source imposes additional constraints on the physical conditions in it. There is also useful information in the time delay regarding, e.g., intergalactic magnetic fields.

Subject headings: acceleration of particles — cosmic rays — gamma rays: bursts

1. INTRODUCTION

The nature of the events that engender cosmic gamma-ray bursts (GRBs) has not been established yet; even their rough whereabouts on the cosmic map is still a moot issue (for a review see Hartmann 1994). While various constraints have been devised regarding physical characteristics of the underlying process, no definite picture has emerged. As is the rule in astronomy, important further clues would be found if the GRB source could be identified as a generator of a different type of signal (e.g., of electromagnetic radiation in the optical region). A similar situation exists regarding the (very few) ultra–high-energy cosmic-ray (UHECR) events of energy higher than 10^{20} eV. The situation concerning optical identification of the sources of UHECRs, some constraints on their origin, and physical conditions in their sources have been recently summarized by Sigl, Schramm, & Bhattacharjee (1994) and by Halzen et al. (1995).

We have set out to check whether a connection can be made between these two types of phenomena. Expecting a time delay, we looked for GRBs that preceded UHECR events by at most a year or two, and that came from the very near vicinity. If the association we conjecture here is confirmed, the constraints that apply to each phenomenon separately can be applied to the other.

2. COSMIC-RAY–GAMMA-RAY BURST ASSOCIATION

In looking for associations with GRBs, we have concentrated on only the most energetic UHECRs, for the following reasons. The higher the energy of a charged cosmic ray (CR), the less its trajectory is affected by intervening magnetic fields and the more practicable it is to associate it with a GRB: First, trajectory wriggling causes the CR to appear from a false

position. Sigl et al. (1994) estimate the disparity in angle to be at most a few degrees for the most energetic UHECRs ($E \sim 3 \times 10^{20}$ eV) (see also § 3), but the expected deflection angle scales in inverse proportion to the energy. Second, since we are interested in correlations with brief, temporal events, we must also reckon with the fact that trajectory wriggling produces a time delay in the arrival time of the CR. We discuss this in § 3, but note here only that for the very highest energy CRs the expected time delay is already of the order of a few months at the minimum, and the delay scales as the inverse square of the energy (and is very uncertain). For lower energy CRs there may be too long a time stretch in which to look for candidate GRBs with any degree of confidence, without refined statistical tools. Third, because the energy of UHECRs degrades quickly with propagation through the intergalactic medium (e.g., Puget, Stecker, & Bredekamp 1976; Hill & Schramm 1985; Sigl et al. 1994), the highest energy ones probably come from nearer by. A GRB that comes from the same source is then expected to be stronger (of higher flux), thus rarer among the GRBs and, in turn, more confidently associated with the UHECR. In general, such events, being more energetic, are also better pinpointed on the sky in both the CR and the gamma-ray regime because of better statistics. (For strong GRBs there is the added bonus that they have a better chance of being detected by the higher energy instruments such as EGRET, with an even better angular accuracy.)

There are very few UHECRs reported in the literature with energies above 10^{20} eV. In the pre-1991 era—for which we have not had available systematic GRB data to search—there is the event detected by the Yakutsk experiment in 1989 May, with an energy of $(1.2 \pm 0.4) \times 10^{20}$ eV (Efimov et al. 1991), and four events from the Haverah-Park experiment (Brooke et al. 1985). We are then left with only two UHECR events

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observed from 1991 onward: The most energetic event ever detected was seen by the Fly's Eye experiment on 1991 October 15, with $E = (3.0^{+0.36}_{-0.54}) \times 10^{20}$ eV (Bird et al. 1993; Bird et al. 1994). The position and error box ($\alpha = 85°2 \pm 1°$, $\delta = 48° \pm 10°$) are shown in Figure 2 of Sigl et al. (1994) in Galactic coordinates. The errors were recently updated to $\Delta\alpha = \pm 0°5$, $\Delta\delta = \pm 6°$ (Bird et al. 1995). The second most energetic UHECR was detected by the AGASA experiment on 1993 December 3, with $E = (1.7-2.6) \times 10^{20}$ eV and position $l = 131°$, $b = -41°$, with an error circle (1 σ) of 1° (Yoshida et al. 1995).

We searched the BATSE catalogs (Fishman et al. 1994; Meegan et al. 1994) for GRBs observed before each of the two UHECR events, and within a few degrees of its reported position.

For the Fly's Eye event (FEE) we found a single BATSE GRB (No. 910503) with overlapping error box, which was observed about 5.5 months earlier (the BATSE record starts only about a fortnight before that). This event happens to be the highest total fluence event in the BATSE catalog, and in all respects it is among the very few brightest GRBs observed to date. It is the 1991 May 3 event that was detected also by COMPTEL (Winkler et al. 1992a), by EGRET (Schneid et al. 1992; Hurley et al. 1994), and by *Ulysses* and *PVO* (Fishman et al. 1994; Varendorff et al. 1992). A maximum photon energy of 10 GeV is reported (Hurley et al. 1994). The best single-instrument position comes from EGRET (Schneid et al. 1992): $l = 171°9 \pm 1°3$, $b = 5°3 \pm 1°1$. That of COMPTEL is (Winkler et al. 1992a) $l = 171°8$, $b = 6°4$, with an error radius of about 3°; all errors are for the 99% confidence level. Time-delay measurements with *PVO* and/or *Ulysses* can give a much better angular definition. Indeed, for GRB 910503, Varendorff et al. (1992) cite a combined COMPTEL-*Ulysses* error box of only $1° \times 1'$, which we find is somewhat outside the updated 1 σ error box of the UHECR but overlaps with the 2 σ box. The different GRB error regions are depicted in Figure 6 of Winkler et al. (1992b).

As to the AGASA event, in its near vicinity (a few degrees) we found no GRBs among the 260 in the first BATSE catalog (recording starts 21 months before the CR event). In the second BATSE catalog (Meegan et al. 1994) we found three GRBs: (1) GRB 920615B (1992 June 15) at $l = 129°2$, $b = -39°62$, which has no quoted fluxes, but the rather large quoted photon-counting positional error of 4°15 indicates that it was not energetic. (2) GRB 920617C (1992 June 17—perhaps related to the previous one), from $l = 131°18$, $b = -41°25$, is also energetically inconspicuous (photon-counting positional error of 5°59). (3) GRB 921230 (1992 December 30—11 months before the AGASA event), with a position $l = 132°91$, $b = -42°87$ (photon-counting positional error of 0°4), is about 3° away from the center of the CR error box. While the GRB statistical position error in this case is small, BATSE is said to have a systematic uncertainty of 4° (Fishman et al. 1994; Meegan et al. 1994). In contrast to GRB 910503, we do not have here the benefit of a more accurate EGRET or COMPTEL position, so the association remains even more tentative. Energetically, GRB 921230 is not in the same league as GRB 910503 (it has a total BATSE fluence about 7 times smaller) but is definitely among the top 10% in fluence.

As explained in § 3, the true position of the UHECR source may be a few degrees off the observed position of arrival, because of magnetic field effects.

Pitfalls of post factum statistics abound in the present case. We believe, however, that the facts as described above cogently bring to mind the possibility that the UHECR event and the GRB are engendered by the same cataclysmic event. At any rate, the exact statistical significance of the association need not be established at this point. More correlations such as those above are expected for future pairs. In fact, some strong GRBs that have been observed recently (e.g., Hurley et al. 1994) may be good candidate precursors for future UHECR events.

3. PROPAGATION EFFECTS

UHECRs are almost certainly extragalactic. Proton seems to be favored as the primary particle that triggers the event (Sigl et al. 1994), but a neutrino cannot be excluded as an atypical primary (Sigl et al. 1994; Halzen et al. 1995). We assume the former in what follows presently; neutrinos will be discussed at the end of this section.

Two effects on an UHECR proton traveling though the Galactic and extragalactic medium have been extensively discussed in the literature, namely, energy loss and angular deflection (for recent accounts see, e.g., the above): A proton with energy above 10^{20} eV loses energy effectively mainly by pion production on diffuse-background, low-energy photons. For example, for an arrival energy of 1.7×10^{20} eV, the initial energy has to be, typically, $\sim 10^{21}$ eV for an origin distance of $D \simeq 100$ Mpc and $\sim 10^{25}$ eV for $D \simeq 200$ Mpc. Such energies are very taxing for any conceivable acceleration mechanism. It is believed, then, that the distance to the sources of the FEE and AGASA events cannot be more than $\sim 100-200$ Mpc. The particles produced by the above processes, especially ultra–high-energy photons produced by secondary π^0 decay, may also be detected on Earth in positional or temporal correlation with GRBs.

The second effect is the change in the apparent direction of the particle due to Larmor curving of the trajectory by intervening magnetic fields. For a homogeneous field, and a constant CR energy, the disparity angle is

$$\theta \simeq \frac{D}{r_L} \simeq 1.6 \left(\frac{D}{3 \text{ kpc}}\right)\left(\frac{E}{10^{20} \text{ eV}}\right)^{-1}\left(\frac{B_\perp}{10^{-6} \text{ G}}\right) \text{deg}, \quad (1)$$

where $r_L = E/eB_\perp$ is the gyroradius for a proton of energy E, and $B_\perp$ is the component of the magnetic field perpendicular to the line of sight. In a tangled field the process is one of random walk in the angle. Within each cell of roughly homogeneous field (of mean size d_c—the reversal length) the spread in angles increases by an amount given by equation (1) with $D = d_c$. The random walk step increases as E decreases along the trajectory, and the effect has to be integrated along the line of sight.

In the context of the UHECR-GRB association, we note that trajectory wriggling also produces a time delay of the CR particle. Unlike the angle deviation, which random walks, the time delay only increases with length of travel. For a homogeneous field, constant energy, and small departure from the line of sight, the time delay is

$$\Delta t \simeq \frac{1}{24}\frac{D^3}{cr_L^2} \simeq 0.3 \left(\frac{D}{3 \text{ kpc}}\right)^3\left(\frac{E}{10^{20} \text{ eV}}\right)^{-2}\left(\frac{B_\perp}{10^{-6} \text{ G}}\right)^2 \text{yr}. \quad (2)$$

(Geometrical factors of the order of a few may enter in other geometries.) In this case Δt is related to the disparity

angle θ by

$$\Delta t = \frac{1}{24}\frac{D\theta^2}{c}. \qquad (3)$$

When the magnetic field is tangled, a simple estimate of the effect can be obtained by picturing the line of sight as divided into segments of mean length d_c over which the magnetic field is constant. The minimum time delay will be produced when the particle returns to the line of sight within each cell (the particle could wander off the line of sight and return only upon arrival, in which case the time delay could be much larger). Then $\Delta t_{min} \sim \int d\,\delta t$, where

$$d\delta t \simeq 0.3 \left(\frac{dD}{3\,\text{kpc}}\right)\left(\frac{E}{10^{20}\,\text{eV}}\right)^{-2}\left(\frac{B_\perp}{10^{-6}\,\text{G}}\right)^2\left(\frac{d_c}{3\,\text{kpc}}\right)^2 \text{yr} \qquad (4)$$

is the delay accumulated over path length dD; we assume that d_c is small compared with the length over which E varies appreciably. The typical time delay is, *roughly*, a factor of D/d_c larger than the above minimal delay.

In principle, propagation effects such as those discussed above may arise in the galaxy hosting the source, in our Galaxy, and in the intergalactic medium (IGM). On the scale of a galaxy there is hardly a loss of energy, so constant E may be assumed in the above estimates. Magnetic field effects in the host galaxy contribute negligibly to the angle disparity (in the present context).

Consider first the contribution of the Galaxy alone. The FEE particle comes roughly from the Galactic anticenter. From Figure 1a of Vallee (1991), which shows a magnetic map of the relevant region, and from his Table 1, we see that it is appropriate to take, approximately, $B_\perp \sim 2\text{–}3\ \mu\text{G}$, and D and d_c of a few kiloparsecs. With the energy of the FEE particle, equations (2) and (4) give a time delay of a few months, consistent with association of the FEE with GRB 910503. Because in this case $D \sim d_c$, the typical delay time is not much larger than the minimum time. The AGASA CR comes from a Galactic latitude of $\sim -40°$, so its trajectory cuts only about 2 kpc through the Galactic disk field (which is said to have a scale hight of ~ 1 kpc; Kronberg 1994), but its energy is smaller, and we expect a similar Galactic time delay (and halo fields may also contribute). The corresponding spread in angles is a few degrees in both cases.

The extragalactic contribution is much more uncertain. In this connection, note that the CR particle is expected to alternate in identity between a proton and a neutron, owing to the pion-producing interactions, so it is only during about half of its journey that it is subject to magnetic field effects. (The chances for identity change in the Galaxy are small, and we can ignore the effect in the above estimate.) Second, because the incremental time delay decreases fast with increasing energy, only the end part of the intergalactic journey contributes appreciably to it (assuming similar magnetic fields along the way). We see from Figure 1 of Sigl et al. (1994), which shows the decrease of energy with travel length, that only about the last 25–50 Mpc need be taken into account; this should be halved because of the proton-neutron alternations.

Very little is known about the intergalactic field at large. Kronberg (1994) cites an upper limit of 10^{-9} G on B and of 1 Mpc on d_c. For these limits, and an effective propagation distance of 25 Mpc, with an energy of 3×10^{20} eV, we obtain from equation (4) a minimum time delay of about 25 yr, while

the typical delay is ~ 600 yr. Thus, confirmation of the association, with a time delay of the order of a year or less, will put stringent constraints on Bd_c, or $B^2 d_c$ for the intergalactic magnetic field. Interestingly, in this context, Plaga (1995) has recently proposed probing intergalactic magnetic fields in the range from 10^{-12} to 10^{-24} G using the (rather shorter) time delay of high-energy gamma rays. His analysis may be relevant to ultra–high-energy photons that are produced by the UHECRs on their way, e.g., from π^0 decay.

If the CR arrives at the Galaxy as a neutron, only propagation effects in the IGM and the host galaxy contribute. The primary CR may, after all, be a neutrino, produced by a proton in the host galaxy. As it propagates subsequently without disturbance, it is expected to arrive without energy loss or angular disparity. The only contribution to a time delay may come from a host galaxy—the neutrino being produced by an accelerated proton, which is subject to the above magnetic field effects in the host galaxy. In this case, one is freed from the energy loss constraint on the distance. Sigl et al. (1994) argue that a neutrino primary can only be an atypical instance, and that for every neutrino event there must be many proton events with similar arrival energy.

4. DISCUSSION

If the GRB-UHECR association is confirmed by future correlations, further insight into the nature of the underlying mechanism can be gained by combining the constraints we deduce separately for the two phenomena. For instance, the position of a strong GRB may be much better defined than that of an UHECR, and, furthermore, the GRB's position can be trusted, since it is not affected by magnetic fields. In the case of FEE and GRB 910503 the combined $1° \times 1'$ error box of the latter is some 10^3 times smaller in area than that of the former. With additional satellites, GRB error boxes may be reduced even further by an order of magnitude or two (as was the case in the 1970s). If it is also confirmed that UHECRs are protons, the energy loss argument greatly constrains the distance of the source. Combined, the two constraints reduce greatly the volume in which to look for counterparts. The deduced maximum distance of 100–200 Mpc for the UHECR source would then become a maximum distance for the nearest (statistically, the strongest) GRB sources. The corresponding luminosity distance of the dimmest BATSE sources would be a few gigaparsecs.

If the GRB event is also to produce UHECRs, the presence of very strong magnetic fields will be implied. What little we know about the physical conditions existing in GRBs during an outburst makes them highly conducive to the acceleration of UHECRs, if they are at cosmological distances. For example, by one class of cosmological origin models, GRBs are produced in differentially rotating disks that are formed by mergers of neutron star binaries (e.g., Paczyński 1986; Mochkovitch et al. 1993; Piran 1994), or by neutron stars that have arisen from accretion-induced collapse (Usov 1992). The magnetic field, B_s, at the surface of these objects may be as high as $\sim 10^{16}\text{–}10^{17}$ G (Narayan, Paczyński, & Piran 1992; Usov 1992; Thompson & Duncan 1993). The angular velocity of these objects is $\Omega \sim 10^4\ \text{s}^{-1}$. The potential difference between the surface of such an object and infinity is (e.g., Ruderman &

Sutherland 1975)

$$\Delta\varphi_{max} = \frac{\Omega^2 B_s R^3}{2c^2} \simeq 1.7 \times 10^{23} \left(\frac{\Omega}{10^4 \text{ s}^{-1}}\right)^2 \left(\frac{B_s}{10^{16} \text{ G}}\right)$$
$$\cdot \left(\frac{R}{10^6 \text{ cm}}\right)^3 \text{ V}, \quad (5)$$

where $R \simeq (1-2) \times 10^6$ cm is the radius of the object. Charged particles that flow away from the surface may be accelerated, in principle, up to the energy $E_{max} \simeq e\Delta\varphi_{max}$, which is more than is needed to produce the observed UHECRs, at a distance of up to ~100–200 Mpc.

Alternatively, particles may be accelerated by relativistic shocks that may be formed in an unsteady relativistic wind (Rees & Mészáros 1994). The maximum energy that may be achieved by protons in the process is (Sigl et al. 1994 and references therein)

$$E_{max} \simeq 10^{17} \left(\frac{Br_{sh}}{0.001 \text{ pc G}}\right) eV, \quad (6)$$

where r_{sh} is the characteristic size of the shock. In our case r_{sh} is about the distance from the compact object to the shock. In the wind, the value of Br_{sh} does not depend on the distance from the compact object, beyond the light cylinder, and is $\sim B_s(\Omega R/c)^3(c/\Omega) = \Omega^2 B_s R^3/c^2$. We can thus see that $e\Delta\varphi_{max}$ with $\Delta\varphi_{max}$ from equation (5) coincides with E_{max} given by equation (6) within a factor of 2 or so.

If GRBs originate nearby—such as in the Galactic corona—it is difficult to see how UHECRs can be accelerated in the same event except by some as yet unknown mechanism.

If, as has been suggested, the intrinsic luminosity of GRBs is rather uniform, and thus fluence is strongly indicative of distance; and if, further, the UHECR luminosity is a given fraction of the gamma luminosity, then we expect the probability of detecting a UHECR in association with a GRB to decrease steeply with decreasing GRB fluence. What is the total energy flux in UHECRs per single outburst? Given that only one particle was observed for each of the two GRBs, we cannot directly estimate this quantity without knowing the probability of detecting an UHECR per GRB. We deduce that this probability, for detectors of the size operating today, is rather smaller than unity, even for those GRBs as energetic as GRB 910503: If one UHECR per GRB was typical, say for AGASA, with its area of about 100 km² (Yoshida et al. 1995), the AGASA event would have indicated a total UHECR fluence of ~3 × 10⁻⁴ ergs cm⁻² at Earth, compared with the total BATSE fluence of GRB 921230 of ~4 × 10⁻⁵ ergs cm⁻². In addition, UHECR energy degrades in travel, so this would have given a high ratio (perhaps as high as 100) of UHECR/GRB energy at the source. This high ratio can be avoided if the probability for AGASA to detect an UHECR for a GRB as energetic as GRB 921230 is at most a few percent; this would correspond to an energy ratio of order unity—not straining further the energetics of the GRB source. More pertinently, this is in keeping with the fact that a few tens of GRBs as strong as GRB 921230 are observed per year, with only one UHECR by AGASA over a few years. GRB 910503 is about 7 times more energetic, and about a few times 10 rarer, so we expect one such burst in a few to be detected in an UHECR. In both cases, detection statistics is consistent with roughly similar energies going into UHECRs and gamma-rays.

A remarkable gamma-ray burst, GRB 940217, was observed on 1994 February 17. The total fluence above 20 keV of ~6 × 10⁻⁴ ergs cm⁻² is twice as high as that of GRB 910503. A photon with an energy of 18 GeV was detected 1.5 hr after the BATSE burst trigger from the region of GRB 940217 (Hurley et al. 1994). This is the highest photon energy ever observed in a burst. The direction is known quite well: a combined COMPTEL-EGRET-*Ulysses* error box of only ~0°.5 × 0°.1. This burst is very promising as a source of UHECRs.

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Note added in proof.—Waxman (Phys. Rev. Lett., in press [1995]) has also suggested recently that UHECRs are produced in GRB cataclysms, but assumes that all spatiotemporal association is washed out by magnetic fields.