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PARTICLE ACCELERATION IN HIGH-ENERGY GAMMA-RAY SOURCES

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ABSTRACT

Many proficient gamma-ray sources show energy spectra that are consistent with E^{-2} primary spectra. Such sources include recently identified gamma-ray quasars and some gamma-ray bursts. Assuming thick target conversion, this is consistent with shock acceleration, and the dominance of the gamma rays of the luminosity is also consistent with previous predictions of high production efficiency of fresh cosmic rays in shocks. The spectral cutoffs in the gamma rays may offer clues as to whether the high-energy particles are electrons or protons. Resolution of this matter might have implications for the nature of the sources and for theory of shock accelerated electrons.

Subject headings: acceleration of particles — gamma rays: bursts — shock waves

1. INTRODUCTION

Many high-energy phenomena display gamma-ray spectra that are roughly E^{-2}. The modest variation can probably be attributed to a variety of astrophysical considerations. In addition to the Galactic gamma-ray background (which is somewhat steeper due to propagation effects), the list now includes gamma-ray quasars and some gamma-ray bursts. These appear consistent with the notion of shock-accelerated primaries. The recent discovery of quasars (Hartmann et al. 1992) that generate gamma rays with an overall efficiency that may exceed 50% is also consistent with the high production efficiencies predicted by shock acceleration theory. Shock acceleration is easily applied to active galactic nuclei. It may be applicable to gamma-ray bursts (see below). Even the gamma-ray pulses from the Crab have E^{-2} spectra. Application to pulsar magnetospheres would be unconventional, though perhaps not entirely out of the question, so the universality of the E^{-2} spectrum may even provide an embarassment of riches.

In addition to the discoveries of *CGRO,* there have been positive detections by ground-based VHE gamma-ray telescopes that may finally be beyond controversy. The discovery of TeV photons from the Crab nebula, now at the 34 σ level, demonstrates the viability of the technique. The emission from the Crab nebula was predicted by Grindlay & Hoffman (1971) many years ago for suitable magnetic fields in the nebula. See also de Jager & Harding (1992). It is merely additional confirmation that particles are efficiently accelerated to trans-TeV energies in the nebula. The most likely model for this is acceleration by a relativistic shock in the pulsar wind.

The other interesting reported discovery, more recent and reportedly at the 6.3 σ level, is TeV γ-ray emission from Markarian 421 (Punch et al. 1992). A second detection has been made more recently (C. Akerlof, private communication). This would imply efficient particle acceleration up to TeV energies, with a high-energy spectral index averaging about -2 in the 10 Gev to TeV range. The failure to detect other gamma-ray AGNs at TeV energies can be attributed to their failure to propagate the longer intergalactic distances without pair producing against cosmic starlight. If the primaries that make the TeV photons are baryonic, prospects brighten for UHE neutrino astronomy, and this makes the nature of the primaries an interesting question.

Another interesting class of VHE energy gamma-ray sources (here VHE is defined to be *COS B* energies and above) is binary Wolf-Rayet winds. Shock acceleration can occur in the reverse shocks formed by the wind collisions. Typically the stronger wind is the W-R so that the shocks are closer to the OB companion. This issue has been discussed by Chen & White (1991, hereafter CW) and by Eichler & Usov (1993, hereafter EU). EU have noted that the gamma-ray spectrum from such objects could be a viable diagnostic of the e/p ratio of the primaries. In this paper, I review the basic predictions of shock acceleration, more recent theoretical work on diffusive shock acceleration of electrons, and applications to various nonthermal VHE and UHE astrophysical systems. Reviews of the observational techniques are not discussed here. The reader is referred to a review by Weekes (1992) for UHE techniques, and to the article by Fichtel in these proceedings for EGRET-range energies.

2. BASIC PREDICTIONS OF SHOCK ACCELERATION

Reviews of shock acceleration include those by Blandford & Eichler (1987) and Ellison & Jones (1991).

The linear theory of shock acceleration (Krymsky 1977; Axford, Leer, & Skadron 1977; Bell 1978; Blandford & Ostriker 1978) predicts a differential spectrum of E^{-2} for subrelativistic shocks and a flatter spectrum for relativistic shocks, or any shock whose compression ratio is larger than 4. The flatter spectrum would be divergent in energy, and even the steeper divergence in the case of nonrelativistic shocks would be logarithmically divergent. This together with observational indications of efficient fresh particle production force the issue of nonlinearity.

Nonlinear effects create some curvature in the spectrum, but for general compression ratio keep the differential spectral index at about -2 over most of the range (Ellison & Eichler 1985). Such a result should generalize to relativistic shocks because the feedback of the particles on the flow should work more or less as in the case of nonrelativistic shocks. A reasonable prediction, then, for observers would be that much of the energy in a violent astrophysical system could end up as high energy particles with a spectral index of about 2, and perhaps a slight flattening at the highest energies. Quantifying this prediction further would require knowing the phase velocity of the waves that scatter the particles near the shock.

The interesting question of the e/p ratio in shock-accelerated particles is still unresolved. On the theoretical side, Levinson (1992) has investigated the question of whether thermal electrons could participate in shock acceleration by self-trapping near the shock via the emission of whistlers. He concludes that they can if the shock Alfven-Mach number exceeds $(m_p/\beta m_e)^{1/2}$. (Here β is the ratio of thermal energy to magnetic energy in the plasma; elsewhere, it is v/c). On the other hand, the electrons are less mobile and are therefore suppressed relative to protons by nonlinear effects (Ellison & Reynolds 1991). Subtle geometric effects discussed by Levinson suggest that this suppression may not be as much as thought naively, since the anisotropy of the turbulence raises the mobility of the electrons relative to that of the protons by a factor of several, but further quantification of these effects would require far more numerical work. Also, the suppression of the electrons raises their mobility, since the amplitude of the turbulence they generate is lower in proportion to their reduced number, so the extent of electron suppression was probably overestimated by Ellison & Reynolds, but the qualitative conclusion that the e/p ratio is low seems to emerge from theory.

3. OBSERVATIONS AND PHENOMENOLOGY

Several classes of cosmic-ray sources are considered in this section: Galactic cosmic rays; gamma-ray quasars and AGNs, gamma-ray bursts, and Wolf-Rayet binaries.

3.1. *Galactic Cosmic Rays*

On the observational side, the e/p ratio in Galactic cosmic rays is low (10^{-2}) and very much consistent with the theoretical discussion such as it exists to date. According to the results of Levinson, the e/p ratio could be higher inside young supernova remnants, where the shocks are strong enough to exploit whistler waves for electron trapping.

3.2. *Gamma-Ray Quasars and AGNs*

That the γ-ray spectra of 3C 279 and related objects do not show any pion decay curvature (D. Thompson, private communication) suggests that the gamma rays are made mainly by electrons (which, in cosmic-ray nomenclature, can include positrons). These could be secondaries, but it remains to be seen whether efficient secondary electron production is reasonable in a dense environment without either causing total degradation of the spectrum or fine-tuning the parameters. Rather than assuming everything happens in the dense part of the jets, it may in any case be easier to invoke a two-stage process: (i) pair production in a sufficiently dense environment, and (ii) acceleration to nonthermal spectra followed by conversion to gamma rays via the inverse Compton process downstream where the jet is less dense. This still begs the question of to what extent the pairs themselves could survive annihilation in the dense environment. One mechanism for pair production could be Blandford-Znajek pair production on magnetic surfaces that connect to a black hole. Depending on the global circuitry, which is beyond the scope of this review, a net current could guarantee survival of either electrons or positrons. Alternatively, dissipative processes, presumably at the base of the jet, would under general conditions yield a fireball with high compactness parameter. The survival of the pairs is not guaranteed under these conditions, but one could perhaps invoke ongoing acceleration by shocks that form on all spatial scales so that particle acceleration and subsequent cascading occur just where the compactness parameter is of order several.

TeV photons from AGNs would be exciting merely as a new discovery. Could they be used as a diagnostic tool for understanding particle acceleration? The energy spectra of gamma-ray quasars in the EGRET range are consistent with shock acceleration theory, which predicts an E^{-2} spectrum over a wide range. The reported TeV gamma rays from Markarian 421 would imply a similar energy spectrum between EGRET and TeV energies.

TeV gamma rays are just near the edge of good transmission (Stecker, de Jager, & Salamon 1992). Within the limits of the modest energy resolution, the gamma rays from Markarian 421 are reported to be consistent with a cutoff at 1.5 TeV. The data are thus consistent with the source spectrum being somewhat harder than the observed spectrum.

TeV gamma rays would also set stronger constraints on electron acceleration than the EGRET gamma rays, so I briefly consider whether it could useful as a diagnostic of the e/p ratio in AGNs. In the absence of radial combining, beaming, or bulk Lorentz boosting, the maximum Lorentz factor to which an electron can be shock accelerated in the presence of inverse Compton losses against a local photon source with luminosity $L_{44} \times 10^{44}$ erg s^{-1} is given by

$$\gamma^2_{\max} = 10^{10}\beta^2 B D^2_{14} L^{-1}_{44} , \qquad (1)$$

where D_{14} is the distance to the source in units of 10^{14} cm and B is the field strength in gauss. B can be as high as $10^3(L_{44}D^{-2}_{14})^{1/2}$ before the synchrotron limit overwhelms the inverse Compton limit. Getting shock-accelerated trans-TeV electrons very near the central engine is thus difficult and would in any case require fine-tuning of the parameters.

Getting the TeV gamma rays out of the dense radiation field near the central engine would be even more difficult. X-rays can pair-produce with TeV photons even at a small relative angle of propagation. At interaction angles of a few degrees, X-ray photons become transparent to TeV gamma rays at a distance of $D_{16} \times 10^{16}$ cm where

$$D_{16} = L_{44}\epsilon_{\mathrm{keV}} , \qquad (2)$$

where $L_{44} \times 10^{44}$ ergs s^{-1} is the luminosity in photons of energy ϵ_{keV} keV, and, while variable, takes a typical value of about 0.2 for Markarian 421 (Makino et al. 1987). The above limit is valid as long as radial combing or bulk Lorentz boosting does not bring the interacting photons below pair production threshold. The condition that the TeV photons not pair-produce against near UV photons raises D by about two orders of magnitude, but because the product of energies is closer to pair production threshold, this constraint is more easily circumvented, e.g., by relativistic beaming. A detailed calculation has been done recently by Dermer & Schlickheiser (1993) that invokes the accretion disk as a source of photons. The list of papers on this matter is growing rapidly at the time of this writing, and a complete set of references is not attempted.

Because the TeV gamma rays must emerge from a region large enough to allow their escape, an upper limit on the baryonic density can be inferred from the condition that the baryonic kinetic energy not exceed the total photon luminosity. This is not a rigorous argument, because we do not know the exact relation between the two quantities, but it is unlikely the kinetic power can exceed the photon power by many orders of magnitude. For Markarian 421 the assumption that the two are comparable gives a baryonic column density that is many orders of magnitude below a radiation length, so it seems unlikely that the TeV gamma rays are made in collisions. This is yet another argument in favor of an inverse-Compton origin, particularly since any pion decay curvature in the spectrum is unlikely to be washed out by secondary bremsstrahlung at these low densities.

It is tempting to presume that the E^{-2} gamma-ray spectrum extending from 100 MeV to a TeV represents thick-target conversion of shock-accelerated primaries. The total photon luminosity, which peaks in the UV or soft X-ray, is of order 10^{44} ergs s^{-1}. The condition that the electrons that emit 100 MeV gamma rays are drained of energy requires that they have individual Lorentz factors in the fluid frame of

$$\gamma_e = 40 D_{16} L_{44}^{-1} \gamma_{\text{bulk}}^5 . \tag{3}$$

This assumes that the photons are comoving with the jet prior to Comptonization. The strong dependence on γ_{bulk} probably limits it to modest values (<10) within the framework of an inverse-Compton model. If the pre-Compton photons enter the jet from the side, they are Lorentz-boosted by γ_{bulk} as well as by γ_e in the jet center of mass, and the conditions on γ_{bulk} are somewhat relaxed.

Similar conclusions can probably be drawn about most of the gamma-ray–bright blazars and OVV AGNs detected by EGRET. The large dynamic range in the energy spectrum of Markarian 421, if the TeV gamma rays are indeed real, and its relatively low luminosity distinguish it and provide particularly strong constraints on the emission models.

To summarize, some of the theoretical problems posed by highly nonthermal gamma rays from AGNs are similar to those posed for gamma-ray bursts, which are discussed just below: The particle acceleration responsible for the nonthermal spectrum is probably required to take place on much larger spatial scales than that of the central energy source; otherwise the compactness parameter is large enough that the spectrum should be degraded to a less obviously nonthermal shape. Several arguments favor electron acceleration followed by inverse-Compton emission over proton acceleration followed by nuclear collisions. If shock acceleration can be established to greatly favor protons over electrons, this could be further taken as evidence that the jet composition itself is pair-dominated (baryon-poor). This does not rule out proton acceleration on smaller scales and the attendant neutrino emission that has been discussed extensively (e.g., Sikora & Begelman 1992 and references within), it merely implies that the particle acceleration has to persist out to larger ones to maintain the nonthermal character of the gamma-ray emission.

3.3. *Application of Shock Acceleration to Gamma-Ray Bursts*

Nonthermal spectra observed by EGRET and COMPTEL in gamma-ray bursts motivate a discussion of particle acceleration in this context. In the cosmological models of GRBs that involve coalescing stellar mass–type compact objects, the blackbody limit on the luminosity from neutron star dimensions at the typically measured photon temperatures of 100 keV is too small to account for the total energetics. This suggests some dissipation mechanism that increases the number of photons at larger scales at the expense of expansion energy. The problem can also be alleviated to some extent by geometric beaming. Such features occur naturally in some models (e.g., Levinson & Eichler 1993), in which the fireball is a baryon-poor jet emerging along black hole threading field lines, through a baryon-rich outlow from a surrounding accretion disk. Instabilities (e.g., Kelvin-Helmholtz at the interface between the two components) and/or unsteadiness in the flow can produce shocks on larger scales, which transfer energy from bulk motion to, ultimately, nonthermal photons.

Shock acceleration of photons has been discussed by Blandford & Payne (1981) in the context of accretion flows. There the photon energy is limited by the inelasticity of the photon-electron scattering. As the number of scatterings required for appreciable acceleration is of order c^2/u_s^2, the acceleration process becomes very inefficient as the photon energy gets to within an order of magnitude of the electron mass. However, in the case of a relativistically expanding fireball, the Lorentz boost can yield photon energies well in excess of $m_e c^2$ as seen by the external observer. Moreover, the shock may be relativistic in the frame of the fluid, such that photons can be accelerated significantly in only a few scatterings, and can attain energies in excess of 100 keV in the fluid frame. This suggests that in the observer frame, an overall Lorentz factor in the bulk expansion of 10^3 could account for a nonthermal spectrum extending out to 100 MeV. Such shocks could result, say, from unsteadiness of the flow parameters, and a broad spectrum of timescales for such unsteadiness is easily imagined. In order that much of the material pass through a shock just below the photosphere, the timescale for unsteadiness in the flow must be

$$\beta t = r_{\text{ph}}(1 - \delta_s)/c . \tag{4}$$

The basic picture, then, is that superthermal photons emerge from the photosphere having just been made nonthermal in the last several cross-shock scatterings just beneath. As the shock approaches the photosphere, the photons fail to be trapped well enough to mediate the shock, and it becomes particle mediated. In principle, it can accelerate pairs to high energies. We define η to be number of gyroradii traversed per e-folding gain in energy near the shock. Synchrotron losses limit the energy of the accelerated pairs to an energy at which they synchrotron emit photons or order $(100/\eta)$ 10 MeV in energy, or about a maximum Lorentz factor in the fluid frame of

$$\gamma_{\max} \approx B_{14}^{-1/2} . \quad (5)$$

Inverse Compton losses limit the maximum Lorentz factor to

$$\beta^2_{\max}\gamma_{\max} \approx \left(\frac{40}{\eta}\right) \times 10^{-1} B T^{-4}_{\mathrm{keV}} . \quad (6)$$

The acceleration time and loss time is far shorter than the hydrodynamic time. Upon being accelerated and getting convected away from the shock, the pairs rapidly lose their energy via the more restrictive of these two processes, i.e., the one that gives the smaller $\gamma_{\max}$, hence the resultant photon spectrum is a "thick-target" one and should resemble the accelerated particle spectrum. The main observational constraint is that at least in some bursts, energies of 100 MeV are easily obtained. The failure to see higher energies is at this point count-limited, and the end of the observed spectrum shows no sign of spectral steepening. Hence the product $\gamma_{\mathrm{bulk}}\gamma_{\max}$ must exceed about 300. For all values of γ_{bulk} usually discussed in cosmological burst models, this is easily satisfied, so that the necessary conditions for particle acceleration do not constrain the burst parameters.

An interesting question is whether the burst spectra could extend up to energies suitable for ground-based detection. (A large-angle ground-based gamma-ray detector has not been designed but is possible in principle.) The problem of resolving the bursts against the atmospheric background would be greatly reduced by the brief duration of the burst. In cosmological models for gamma-ray bursts, the photospheric temperatures in the fluid frame are expected to be of order 10 keV, and B can be as high as 10^6–10^9, so that equations (5) and (6) allow Lorentz factors, still in the fluid frame, of up to 10^3. Bulk Lorentz factors of up to 10^3 have also been discussed, though the GRB spectra, which typically have temperatures of order 100 keV, suggest more modest values of order 10. It would thus strain burst parameters to suppose the spectra continued up to a TeV, but it is not entirely out of the question.

Ions could be accelerated to higher energies. Deep beneath the photosphere, the dominant loss mechanism for ions would be nuclear collisions, so that the possibility arises that a significant fraction of the fireball energy could be dissipated as neutrinos. We find, however, that the next generation of detectors is unlikely to detect bursts with the possible exception of the very largest ones (total fluence $\sim 10^{-3}$ ergs cm^{-2}).

A widely known constraint on cosmological models of gamma-ray bursts is that the fireball must not be mechanically loaded by baryons. On the other hand, the typical neutrino luminosity associated with neutron star formation or coalescence is enough to drive a baryonic wind (Duncan, Shapiro, & Wasserman 1986) that is three to four orders of magnitude larger than the minimum needed to quench the burst (Levinson & Eichler 1993). The discrepancy bears some similarity to the evidence for pair domination of jets in AGNs cited above. In each case, baryon purity could result from the fact that the jets emerge along field lines that connect to an event horizon. The pairs are somehow created on these field lines, say by the Blandford-Znajek process or, in the case of neutron star mergers and the like, ν–$\bar{\nu}$ annihilation. The event horizon is then given a qualitative role in the creation of the phenomenon, and general relativity enters astrophysics well beyond the level of post-Newtonian corrections. In this interpretation, it is conceivable that if event horizons did not exist, neither would cosmological gamma-ray bursts.

3.4. *Wolf-Rayet Binaries*

The high-energy γ-ray cutoff as acceleration diagnostic has been discussed in the context of Wolf-Rayet OB binaries (EU). Any inverse-Compton γ-radiation from these systems can be interpreted with particular advantage because the optical-UV photon spectrum, the shock parameters, and shock location are known quite well by astrophysical standards. The nonthermal radio emission implies relativistic electrons, though it is not entire clear, given the high column density at the acceleration sites, that the electrons are primaries. The time dependence of the nonthermal radio emission has been explained very elegantly by Usov (EU) who notes that at certain orbital phases the acceleration site is obscured by the radio photosphere of the wind. Applying equation (1) to a typical Wolf-Rayet binary, such as the prototype WR 140, one obtains a maximum value of γ^2 of about 3×10^7 and, with a mean initial photon energy of 10 eV, a maximum photon energy of about 200 MeV. This is within the EGRET range and the detection by EGRET of such a γ-ray spectrum with a suitably located high-energy cutoff would support the idea that these are inverse-Compton scattered by electrons. A suitable observed dependence of the high-energy cutoff on orbital separation would support this conclusion further, though the exact nature of such a dependence depends on the field geometry in the wind. By contrast, pion decay γ-rays would have a low energy cutoff, and the conversion efficiency would have a stronger dependence on orbital separation. At the time of this writing, it remains to be seen whether EGRET will detect WR 140 and related systems. It is interesting that the γ-ray source 083+03, which is about 2° from WR 140 and could plausibly be identified with it (though being just outside the error box) was observed by *COS B* to be on during the 1978 periastron passage, but not at other times. The implied particle acceleration efficiency is extremely large, and independent confirmation is crucial. The most recent periastron passage of WR 140, which occurred at 1993.2, was a critical observation period, and published results are eagerly awaited.

4. CONCLUSIONS

VHE gamma-ray sources, including many γ-ray bursts, have spectra and efficiencies that are consistent with a shock-accelerated origin of the primaries. The gamma-ray data—in particular the absence of pion decay curvature in the spectrum—may be constraining enough to serve as diagnostics of the primary electron to proton ratio. Time correlations of TeV outbursts with those at EGRET energies would probably be significant; among other things, they would suggest a common origin and inferences about the primary spectrum would thus be more justified.

Theoretical work points toward a low e/p ratio when the plasma does not contain pairs, which is encouraging for neutrino astronomy. But the thermal plasma from which particles are accelerated may be pair dominated.

For Wolf-Rayet binaries, EGRET observations could be a good diagnostic of the *e*/*p* ratio. Because they typically have elliptical orbits, it is important that they be observed at and near periastron, when conversion efficiencies are likely to be the highest.

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