POWER-LAW SPECTRA FROM FERMI ACCELERATION AT RELATIVISTIC SHOCKS

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The theory of diffusive acceleration at shock fronts, which applies only if the fluid speed is *nonrelativistic*, yields a simple formula for the power-law index s of accelerated particles: $s = 3r/(r-1)$, where r is the compression ratio of the shock front. Although the acceleration process depends on there being effective pitch-angle scattering of the particles in both the upstream and downstream regions, no property associated with this process appears in the formula. Unfortunately, if the velocity of the fluid through the shock front is *relativistic*, as seems to be the case in the central engines of AGN's, and also in some hot-spots in the outerparts of their jets, this attractive property ceases to hold. To find the index s, it becomes necessary to develop specific models describing the scattering process. The physical reason for this is that the particle distribution close to a relativistic shock is anisotropic. The exact type of anisotropy depends on the properties of the pitch angle scattering and determines both the average energy gain per shock crossing, as well as the probability of escape downstream. In this paper, results are presented for the pitch angle diffusion resulting from scattering in a weakly turbulent plasma with a Kolmogorov spectrum of Alfvén waves moving parallel and antiparallel to the magnetic field. This kind of spectrum has been employed in nonrelativistic models of hot spots [1]. However, the results obtained tend not to vary too dramatically as a function of the turbulence spectrum, being less than about 0.2 in the resulting s (0.1 in the predicted synchroton spectral index) for turbulence spectra between k^{-1} and k^{-2} [3].

Another of uncertainty in the predicted power law index of accelerated particles lies in the structure of the shock front. Even if we assume the shock to be a simple discontinuity in the velocity, there are several possibilities for the jump conditions. For example, if the shock deposits most of the incoming kinetic energy into thermal motion of the ions, the compression ratio of a strong shock remains close to 4, producing a power law index $s \approx 4$ even for high upstream speeds. On the other hand, if electron pressure plays a role, or if pairs are created in the downstream plasma, the equation of state softens, the compression ratio increases and the spectrum of accelerated particles hardens. Several papers on relativistic shocks may be found in the literature (e.g., [5]) but each limits itself to particular cases such as that of an ultrarelativistic shock, or uses approximations concerning the equation of state of the fluid. Here, results are presented for four different physical situations which could occur behind a relativistic strong shock. In the first, the kinetic energy of the fluid (which consists of fully ionized hydrogen and helium – 25% by mass – together with the associated electrons) is deposited into the ions. In the second case, energy is thermalized amongst the electrons. The third case assumes that the downstream plasma contains electron/positron

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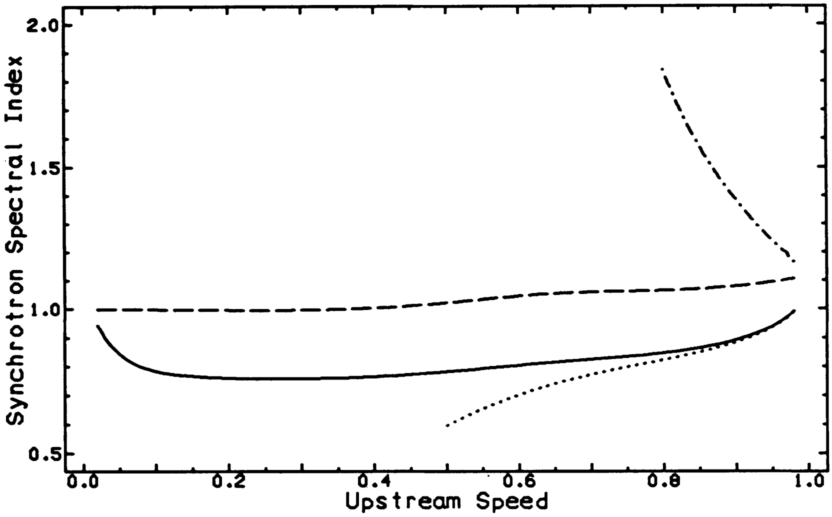

The spectral index of synchrotron radiation expected from shock accelerated electrons, assuming that the region over which these electrons cool is unresolved by the observer (without cooling, the spectrum is 0.5 harder). The dash-dotted line corresponds to a relativistic gas. The dashed line is for a strong shock with only ion pressure supporting it, the solid line for support by electron pressure only. The dotted line is for a strong shock with pressure provided by electrons and pairs, the number of these being approximately 100 per proton In each case a Kolmogorov ($k^{-5/3}$) spectrum of Alfvén waves is assumed.

pairs, and the fourth case is that in which both the upstream and downstream fluid can be described by the equation of state for a relativistic gas: $E = 3P$.

The method of calculation is a generalization of that described in [4] and has much in common with that used in applications involving interplanetary shocks. A full description and presentation of results may be found in [3]. A slightly different version is presented by Heavens and Drury [2].

Results are shown in the figure for each of the possible jump conditions. The pitch angle diffusion coefficient is that obtained for a Kolmogorov spectrum of Alfvén waves in which the nonlinear effects on the orbits of particles moving almost perpendicular to the magnetic field have been modelled by using a constant diffusion coefficient when $\mu < 1/30$ (where μ is the cosine of the particle's pitch angle) (see [3]). Changing the pitch angle diffusion coefficient produces a difference $\lesssim 0.2$ in this index. The effect of the jump conditions can be seen in the figure to be larger, but decreases as $u_- \to 1$.

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