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INTERPLANETARY ORIGIN OF ENERGETIC PARTICLES*

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It has become evident over the past 15 years that energetic charged particles (of both signs) are produced wherever and whenever there is sufficiently vigorous agitation of a tenuous ionized gas. On a laboratory scale, fast particles are produced in the plasma pinch.[1-5] On a planetary scale, energetic particles are produced in the region of impact of the solar wind against the outer boundary of the geomagnetic field and in the geomagnetic field itself.[6-8] The aurora is the visible manifestation of these particles. On a stellar scale, energetic particles are produced in association with the solar flares[9-12] and in supernovae ejecta.[13-17] On a galactic scale, fast particles are produced in extraordinary quantities in quasars and radio galaxies.[18-22] The general cosmic-ray phenomenon, observed in the solar system, is evidently the background level of fast particles from all such sources. Altogether it appears that some fraction of the energy stirred into an ionized gas reappears in the form of a relatively small number of very fast particles.

The mechanism by which the fast particles have been accelerated is not known, though a number of interesting ideas have been suggested.[23-26] The important point is that, whatever the mechanism, the generation of fast particles by sufficiently agitated plasmas appears to be a general rule on any scale of laboratory size or larger.

Now, as already noted, energetic particles are produced in the solar system at the sun and in the vicinity of the magnetic field of Earth. It is our purpose here to point out that there is, in addition, an important interplanetary source of energetic particles. The basis for this assertion is the general rule of fast-particle production in agitated plasmas. Irregular plasma motions in interplanetary space may occur when the general coronal temperature varies with solar longitude and/or with time.[27] But to take the strongest case, a large flare on the sun is usually followed by coronal enhancement and a sudden increase in the strength of the solar wind. The large-scale hydrodynamic nature of the solar wind means that a sudden increase in the wind at the sun takes the form of a blast wave[28] in space. At the front of the blast wave, where the wave is piling up the slower quiet-day wind ahead, there is an abrupt and violent "shock" transition.[28,29] The speed of propagation of the "shock" is $(1\text{-}2)\times 10^3$ km/sec. The gas density in the blast wave may be as much as $30/\text{cm}^3$,[30] compared to the quiet-day values of $(2\text{-}15)/\text{cm}^3$.[31,32] The quiet-day magnetic fields, of $(3\text{-}7)\times 10^{-5}$ gauss,[33,34] must be compressed along with the gas to something in excess of 10^{-4} gauss.[28,35] The total energy of the blast wave is typically 10^{32} erg. Such a shock transition, and the associated disordered motions, are much more violent than the quiet-day standoff "shock" upstream from the geomagnetic field, where a $10^{10}/cm^2$ sec flux of electrons above a few keV and a $10^6/cm^2$ sec flux above 30 keV are produced.[5-8] Indeed the interplanetary blast wave has energies and velocities which are more like those associated with the solar flare. The solar flare is known to produce relativistic electrons and occasionally even relativistic ions. Consequently, the blast wave should be a vigorous source of energetic charged particles.

Now, energetic interplanetary particles should be most intense in the regions where they are produced. Therefore, they are expected in the disorder between regions of fast and slow wind, and in much more copious supply in the blast wave following a large flare.

Energetic particles of interplanetary origin may already have been observed in the unusual increase of protons below 15 MeV on 30 September 1961 in coincidence with the passage of the blast wave originating at the sun on 28 September. The observations[36] were carried out from Explorer XII. On 30 September the proton flux (9-14 MeV) was declining from the earlier peak produced by the flare of 28 September. With the arrival of the blast wave (as indicated by the onset of a Forbush decrease and the sudden commencement of a magnetic storm) the proton flux increased abruptly by more than a factor of ten, to about $10^2/cm^2$ sec steradian. This increase lasted only for a period of several hours (during the active phase of a geomagnetic storm) after which the proton flux returned to the smoothly declining curve which it has been following prior to the arrival of the blast wave. We suggest that the particles producing this transient burst were of interplanetary, rather than solar, origin. For suppose that they were of solar origin: Adiabatic deceleration in the expanding volume of the blast wave rules out the possibility that the additional energetic particles were conveyed all the way from the sun in the wave. Further, the fields in the forward regions of the blast wave, where the particles were observed, were not fields which had been conveyed directly from the sun. Rather the fields were interplanetary fields piled up ahead by the enhanced wind behind.[28] So there is no reason to expect to find solar particles concentrated in them. Suppose, then, that the additional protons were released continuously from the sun and their outward passage was merely impeded by the compressed fields of the blast wave. But if this were the case, the entire region behind the front of the blast wave would have been filled with the particles, and not just a thin region at the head as was observed. Thus, the only possibility for solar origin is to assume that there was a transient burst from the sun on 30 September, two days after the flare, which by coincidence arrived at Earth at the same time as the blast wave and which had a characteristic decay time much shorter than the protons from the flare on 28 September. This seems rather artificial. Instead we suggest that the observed proton intensity increase on 30 September 1961 was of interplanetary origin.

In conclusion, then, we point out that energetic particles should be produced in violent interplanetary plasma phenomena. It is suggested that intense fluxes of energetic particles of interplanetary origin have already been observed on at least one occasion.[37]

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[37]A similar increase in the low-energy proton intensity, in coincidence with the passage of a blast wave, was observed on 12 November 1960 [J. F. Steljes, H. Carmichael, and K. G. McCracken, J. Geophys. Res. 66, 1363 (1961)]. The increases proton intensity may have been partly or wholly of interplanetary origin, but the increase was of such a form that it is not possible to rule out a solar origin.

GRAVITATIONAL COLLAPSE AND SPACE-TIME SINGULARITIES

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The discovery of the quasistellar radio sources has stimulated renewed interest in the question of gravitational collapse. It has been suggested by some authors[1] that the enormous amounts of energy that these objects apparently emit may result from the collapse of a mass of the order of $(10^6\text{-}10^8)M_\odot$ to the neighborhood of its Schwarzschild radius, accompanied by a violent release of energy, possibly in the form of gravitational radiation. The detailed mathematical discussion of such situations is difficult since the full complexity of general relativity is required. Consequently, most exact calculations concerned with the implications of gravitational collapse have employed the simplifying assumption of spherical symmetry. Unfortunately, this precludes any detailed discussion of gravitational radiation—which requires at least a quadripole structure.

The general situation with regard to a spherically symmetrical body is well known.[2] For a sufficiently great mass, there is no final equilibrium state. When sufficient thermal energy has been radiated away, the body contracts and continues to contract until a physical singularity is encountered at $r=0$. As measured by local comoving observers, the body passes within its Schwarzschild radius $r=2m$. (The densities at which this happens need not be enormously high if the total mass is large enough.) To an outside observer the contraction to $r=2m$ appears to take an infinite time. Nevertheless, the existence of a singularity presents a serious problem for any complete discussion of the physics of the interior region.

The question has been raised as to whether this singularity is, in fact, simply a property of the high symmetry assumed. The matter collapses radially inwards to the single point at the center, so that a resulting space-time catastrophe there is perhaps not surprising. Could not the presence of perturbations which destroy the spherical symmetry alter the situation drastically? The recent rotating solution of Kerr[3] also possesses a physical singularity, but since a high degree of symmetry is still present (and the solution is algebraically special), it might again be argued that this is not representative of the general situation.[4] Collapse without assumptions of symmetry[5] will be discussed here.