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We wish to discuss the possible role of the betatron effect as a mechanism for the acceleration of cosmic particles to relativistic energies. We propose that this mechanism can be extremely efficient in a region where the magnetic field is zero, or very small compared with time-dependent magnetic fields in nearby regions. This brings us to a possible model for extragalactic radio sources, which is briefly outlined.

If the zero-field condition is not met, the betatron mechanism is rather inefficient. For instance, the gain of momentum of a particle in a homogeneous magnetic field that is slowly increasing with time is given by[1]

$$p(t)/p(0) = [B(t)/B(0)]^{1/2} \quad .$$

In a given acceleration event the particle therefore gains a certain fraction of its initial momentum.

The inefficiency of the betatron mechanism is paradoxically connected with the very existence of a magnetic field. The magnetic field causes the particles to spiral, and therefore limits the amount of magnetic flux that their orbits encircle, while the acceleration effect is directly proportional to the time derivative of this flux.

These difficulties do not apply in a region where the magnetic field is zero or negligible, and the electric field produced by time-dependent magnetic fields in other regions of space can cause acceleration unhampered by spiraling.[2] To be more definite, let us consider a model of the betatron mechanism operating in the vicinity of an astronomical object, which could be a star, or a galaxy.

The magnetic field in the free space surrounding our object should be roughly described as the field of a dipole $\underset{\sim}{D}$ centered in the object, plus some slowly varying field $\underset{\sim}{B}_0$ due to other objects in the universe.

Let us consider a particularly simple case in which $\underset{\sim}{B}_0$ is uniform and parallel to $\underset{\sim}{D}$. In this case the field in the median plane has only a z component,

$$B_z = B_0 - \frac{D}{r^3} = B_0 \left(1 - \frac{r_0^3}{r^3}\right).$$

The field is zero at $r = r_0$, and particles of any momentum can be accommodated in circular orbits in the region $r > r_0$ (see Fig. 1).[3]

It is easily seen that these orbits are stable against radial oscillation but unstable against vertical oscillation,[4] so that any particle accelerated near the median plane is lost after a number of turns. This mechanism can be of interest if the time scale of the effects that produce the acceleration of the particles is comparable to the time in which they complete a few revolutions.

The mechanism of acceleration could be the following: Suppose that the central "object" is undergoing some catastrophic event; it is conceivable that during this event the strength of its dipole $\underset{\sim}{D}$ undergoes some variation. This will cause betatron acceleration of the charged particles in the free space around that object itself. In the spirit of our simple model, let us assume the direction $\underset{\sim}{D}$ to be constant[5] and parallel to $\underset{\sim}{B}_0$, with only its strength increasing with time. In the median plane this will cause a magnetic field,

$$B_z(r,t) = B_0 - D(t - \frac{r}{c})/r^3 ,$$

and a tangential electric field,

$$E(r,t) = D(t - \frac{r}{c})/r^2 c .$$

A particle initially in a region where $\underset{\sim}{B} \neq 0$ spirals around without gaining much energy. On the contrary, the particles initially near the median plane at r_0 experience the full accelerating effect of the electric field and are injected in circular orbits near the zero-field region.[6] When D increases, the zero-field region moves outward. The particles already in circular orbits are accelerated, and their orbits expand and precede the zero-field region in its outward motion. At the same time new particles are caught up by the zero-field region and are injected into circular orbits. In this way, most of the particles initially in a washer-shaped region near the median plane are accelerated and radially focused in a region neat the instantaneous value of r_0, independent of their initial conditions.

A rough estimate shows that a particle captured in the zero-field region at $t = 0$ with a small initial momentum has at a time t a momentum

$$p \approx 3eB_0[r_0(t) - r_0(0)];$$

if r_0 increases by 50%, we have particles of any energy between 0 and approx. $eB_0r_0(t)$. From this model it is quite clear that a zero-field region can provide an efficient method of continuous injection and acceleration. It is rather instructive to contrast our case to that in which $\underset{\sim}{B}_0$ is antiparallel to $\underset{\sim}{D}$. In the median plane B_z is now everywhere positive, and for $r > (2\ D\ B^{-1})^{1/3}$ we have completely stable orbits. The lack of a zero-field region, however, prohibits any simple and efficient mechanism for the injection into circular orbits. What energies can be obtained if our model is applied to a star or to a galaxy? In the case of a star inside our galaxy, we can assume $B_0 \approx 10^{-6}$ G instantaneous values of r_0 of the order of one light year and get energies of the order of 10^{13} to 10^{14} eV. In a galaxy, we could assume $B_0 \approx 10^{-8}$ G (the intergalactic space), and $r_0 \approx 10^5$ light years, which would then give energies of the order of 10^{16} to 10^{17} eV.

The spectrum of energies obtained through this mechanism in a single event would be decreasing, because of the spilling of particles owing to the vertical instability.[4] The shape of the spectrum is therefore expected to depend critically on the rate of change of the dipole strength. The actual spectrum of the cosmic rays produced by many independent events of this kind would depend on the distribution of values of B_0 and r_0 in the individual events.

We have studied here only a rather particular case, but there is some latitude in the possible design of such cosmic accelerators. In a dipole field expanding against a background field, for example, we can admit some angle between $\mathbf{B}_0$ and $\mathbf{D}$, or some inhomogeneity of $\mathbf{B}_0$. Because the main ingredient seems to be the existence of a zero-field region, efficient acceleration can also arise in other magnetic configurations, as, e.g., the field of two magnetic dipoles of comparable strength and nearly antiparallel, one or both of which is rapidly time dependent.

It is an interesting possibility that the mechanism considered here could be related to the occurrence and structure of some peculiar extra-galactic radio sources. Some of these sources apparently consist of two radiating regions on opposite sides of a visible object (often a galaxy), and at large distances from it.[7]

In the model--considered before--of an increasing dipole plus a constant field, we have an efficient method of transferring energy to particles near the zero-field region, which can be well outside the boundaries of the object that produces the dipole field. The accelerated particles form a loop current around the central "object". This current produces a magnetic field, which can give rise to the following effects:

(a). It provides containment, which causes the orbits to be stable against vertical, as well as radial, betatron oscillations.[8]

(b) The magnetic field produced by the current reduces the size of the "zero-field" region, and prevents the injection of new particles into circular orbits and their acceleration to high energy.

The first of these effects insures stability of the current against the more obvious losses.[9] The second effect is also important: After the first stage, during which the loop current of highly relativistic particles is produced, energy can be transferred by the electric field to particles of lower energy that spiral along the lines of the magnetic field surrounding the current. It is easy to see that such particles radiate preferentially in forward and backward directions with respect to the current. The radiation of the ring source is highly anisotropical and is highest near the plane of the loop. An observer in this plane (or near it) then sees the radiation coming mainly from two opposite regions of the loop.

The quantitative problems connected with this model are now under investigation. The model seems to explain some of the more striking peculiarities of the sources, like the double structure and the distance from the main visual object. The anisotropy of the source, which follows from the model, can be very useful in decreasing the previous estimates of the total power emmitted.[10]

I am very grateful to Dr. B. Coppi for an interesting discussion, and to Dr. David L. Judd for pointing out the possible importance of the self-field of the accelerated particles.

FOOTNOTES AND REFERENCES

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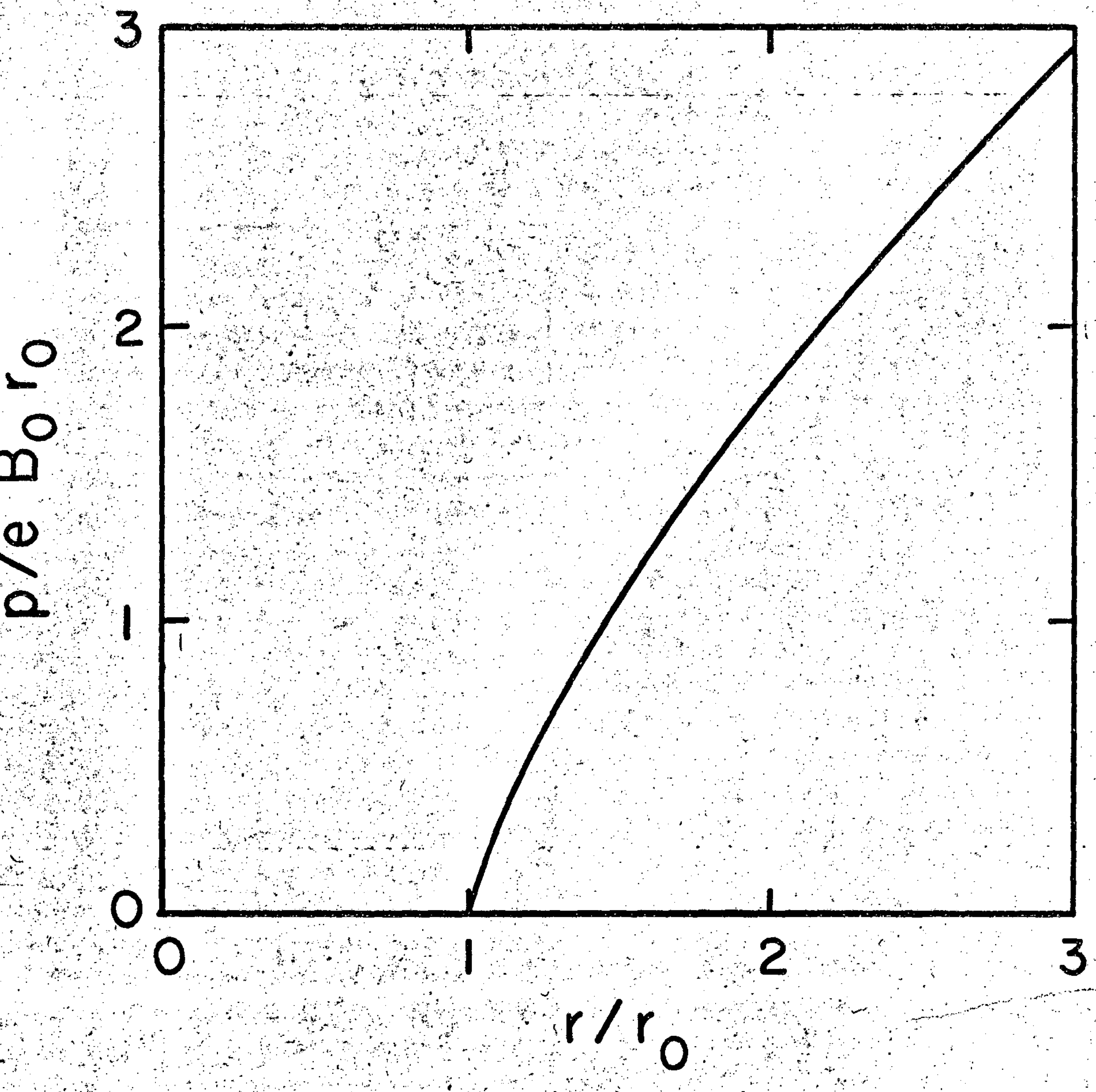
1. This equation applies if the particle moves orthogonally to the magnetic field.
2. The importance of "zero field" regions has already been stressed before, especially in connection with the problem of solar flares; see R. G. Giovannelli, Monthly Notices Roy. Astron. Soc. 107, 338 (1947).
3. Another set of orbits is also available for $r < r_0$, for particles rotating in an opposite direction.
4. This could be modified by the magnetic field of the rotating particles, as discussed later.
5. This seems reasonable, as the direction of $\underset{\sim}{D}$ should be closely related to that of the (constant) angular momentum of the object.
6. Particles of opposite charge, like electrons and protons (or light nuclei), will be injected into the same family of orbits with $r > r_0$, but will rotate in opposite directions.
7. For an extensive survey, see P. Maltby and A. T. Moffet, Astrophys. J. Suppl. 67, Vol. 7, 141 (1962).
8. The application of these focusing properties to particle accelerators has been proposed by G. J. Budker, CERN Symposium, Geneva, 1956, Vol. I, 68.
9. The stability of intense currents of relativistic particles against "plasma" instabilities is still an open problem. Our situation is quite different from that of a plasma accelerator (see reference 8), or

thermonuclear devices, see N. C. Christofilos, Second United Nations International Conference on Peaceful Uses of Atomic Energy, Vol. 32, paper 2246.

10. Observational data seem to exclude the hypothesis of toroidal sources with isotropic emission, see reference 7.

FIGURE CAPTION

Fig. 1. The momentum of a particle in a circular orbit as a function of the radius of the orbit. All particles with $0 \leqslant P \ll e B_0 r_0$ are piled up between r_0 and approx $1.5\, r_0$.



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