increase in counting rate above background at altitudes below 500-600 km over South America. The observations from the cosmic ships in 1960 seem to suggest that the lower boundary of the inner zone is now closer to the earth than two years ago.

Vernov, S.N.: During the flight of the 2nd Soviet cosmic ship in 1960 it was determined, that in the region of Brazil anomaly the intensity of protons of the inner radiation belt is 2 particles/cm²/sec.

At the same time on the same latitudes outside the Brazil anomaly the intensity of radiation is at least 2-3 times less. During the flights of American satellites the intensities is less than this quantity.

This is undoubtedly of great interest, because it shows the changes of cosmic space (perhaps air density) from 1958 to 1960 in connection with changes of the activity of the sun.

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-2-13. Nature and Origin of Radiation Belts

S. F. SINGER

Department of Physics, University of Maryland, College Park, Maryland, U.S.A.

Recent developments in the neutron albedo theory are reported and the results are compared with observational data.

Protons. The calculated energy spectrum agrees extremely well with the observed spectra, provided nuclear interactions (Freden and White) and an anisotropic emission of albedo neutrons (Lenchek and Singer) are taken into account. The spatial distribution is calculated on the basis of the determination of geometric injection coefficients. The lifetime is assumed to be controlled by exospheric densities close to the earth and determined by the breakdown of the adiabatic invariance of magnetic moment at larger distances. This leads to a maximum intensity at about 1½ earth radii and a virtual disappearance of protons at about 2 earth radii. The absolute intensities of trapped protons calculated from neutron albedo theory and the most reasonable exospheric models are in very good agreement with observations in nuclear emulsions.

Electrons. From neutron albedo we calculate properties of the resulting trapped electrons. The lifetime is a particularly challenging problem. We conclude that only a fraction of the observed trapped electrons can be of neutron albedo origin, possibility most of the high energy electrons, *i.e.*, above 500 kev. The remainder, and particularly the large bulk of low energy electrons are locally accelerated, with the energy ultimately derived from the sun.

Introduction

The purpose of this paper is to review the successive refinements which have occurred in the neutron albedo theory and to compare the results of the theory with available observations. It is quite important to carry the theory forward as far as possible since only in this way can one establish its validity. It must be realized that agreement of the theory with observation is only a *necessary* but not a *sufficient* condition to establish its validity. In other words, there may exist some other injection mechanisms into the geomagnetic field which might account for a good portion of the trapped particles. In the case of the trapped protons, we have not been able to find any other injection mechanisms which would give an appreciable trapped proton flux, and furthermore the neutron albedo theory fits the observations extremely well.

The subject has been recently reviewed by Singer and Lenchek[1] in an article being published in *Progress in Cosmic Ray Physics*, (J. G. Wilson, Editor) Vol. 6, North-Holland Publ. Co. 1962. More detailed papers on the trapped protons have been written by Lenchek and Singer[2] JGR, 1962; and on the electrons by Lenchek, Singer and Wentworth[3] in J. Geophys. Research, 1961.

Trapped Protons

We treat the trapped protons which result from galactic cosmic rays as a steady state problem in which the injection rate is balanced by the loss rate. In the initial development of the theory the injection was calculated from the decay of albedo neutrons and the loss was assumed to be due entirely to interactions with the earth's exosphere. In later developments (Welch and Whitaker,[4] 1959; Singer,[5] 1959; Dragt,[6] 1961; and Wentzel,[7] 1961), the breakdown of the adiabatic invariance of magnetic moment was also considered. It is clear that in order to construct a precise theory, one has to have as good a knowledge as possible of the injection spectrum of protons from the albedo neutrons and of the properties of the atmosphere.

We derived our neutron albedo spectrum by considering the knock-on protons produced by high energy cosmic rays in the upper atmosphere. A study of such knock-on protons has been made by the Bristol group using nuclear emulsions (Camerini, Fowler, Lock and Muirhead,[8] 1950). It is clear that the knock-on neutrons which, of course, are not seen in the emulsion should have an energy spectrum similar to that of the protons above energies of the order of 50 Mev. From this data we derived an energy spectrum for the upward emitted neutrons as $E^{-1.8}\,dE$. An energy spectrum derived by Hess, Canfield and Lingenfelter[9] (1961) by a different method is in close agreement with our value. In a recent development of the theory we have considered also the effect of the anisotropic emission of these neutrons. The very highest energy neutrons are emitted only at directions which are nearly tangent to the atmosphere, while at lower energies, of the order of 50 Mev, the neutrons are emitted nearly isotropically. The effect of this anisotropy is to change the effective energy spectrum of the neutrons which are able to inject protons into trapped orbits. The spectrum is steepened and becomes $E^{-2.9}$.

The protons resulting from neutron decay

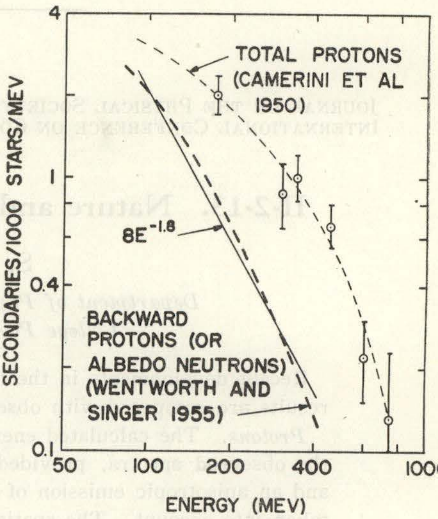

Fig. 1. Energy spectrum of protons generated in high energy stars (CNO group) in emulsions (Wentworth and Singer, 1955) based on data of the Bristol group (Carmerini *et al*, 1950, 1952).

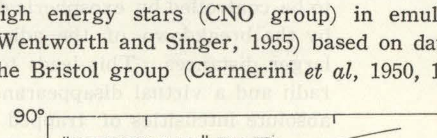

Fig. 2. Angular distribution of albedo neutrons. In this model the cone of half-angle $\varphi(E)$, centered on the zenith, is assumed to be empty of neutrons having energy $>E$. In the directions lying between this cone and the horizon plane the intensity is uniform *vs.* zenith angle and has the spectrum $E^{-1.8}\,dE$.

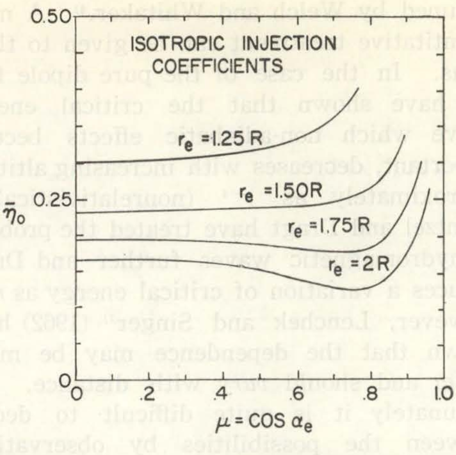

Fig. 3. Pitch angle dependence of the "Isotropic" injection coefficient $\bar\eta_0$ for several lines of force. The isotropic injection coefficient represents the fraction of the spiral orbit along which injection is possible, assuming an isotropic neutron albedo from the earth. The anisotropy of the albedo modifies the injection coefficient, leading to the result that the total injection coefficient is $\bar\eta(r_e,\alpha_e,E)=\bar\eta_0(r_e,\alpha_e)(E/50)^{-1.1}$ for $E>50$ Mev.

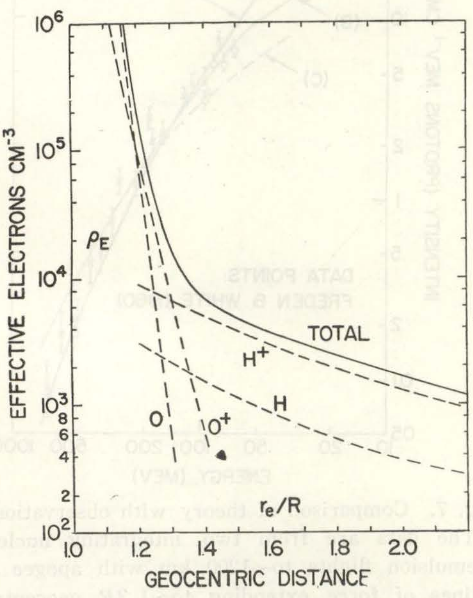

Fig. 4. Effective density of free electrons near the earth. For each constituent we plot the equivalent (with respect to energy dissipation rate) density of free electrons. A temperature of 1500°K is assumed at the base of the exosphere. To convert from ρ_E to actual densities (atoms cm^{-3}) divide each component by the appropriate factor: H^+, 1.00; H, 0.47; O^+, 3.74; O, 3.22.

carry the kinetic energy of the neutrons at these very high energies, and they will therefore have a similar energy spectrum, namely $E^{-2.9}$.

Fig. 1 shows the energy spectrum of the upward emitted neutrons. Fig. 2 shows the angular distribution. Fig. 3 shows the calculated injection rate as a function of geocentric distance and equatorial pitch angle.

Next we must specify the loss mechanisms more precisely. To do this we must adopt a model of the exosphere. For a variety of reasons we have chosen a model shown in Fig. 4. which accords well with satellite data at lower altitudes and has been extrapolated using a theory of the neutral exosphere (Öpik and Singer,[10] 1961). The ionized component at high altitudes is deduced from Whistler results (Smith and Helliwell,[11] 1960). A more detailed discussion of the reasons for choosing this model of exosphere is given elsewhere (Singer,[12] 1960). A crucial question is whether the atmospheric density really controls the trapped particle density, at least at low altitudes close to the equator, as we had originally assumed. I think we can now safely affirm this point. In the first place, the results of Vernov (Vernov, Grigorov, Logachev and Chudakov,[13] 1958) (Fig. 5) clearly show a rise in intensity starting at around 500 km, where one indeed would expect the intensity to increase. This phenomenon is shown more clearly in data obtained by Yoshida, Ludwig and Van Allen[14] (1960) Fig. 6. Note particularly the change in slope at about 1,000 km as was predicted (Singer,[15] 1958). This is due to the fact that atomic oxygen ceases to be the most important constituent of the exos-

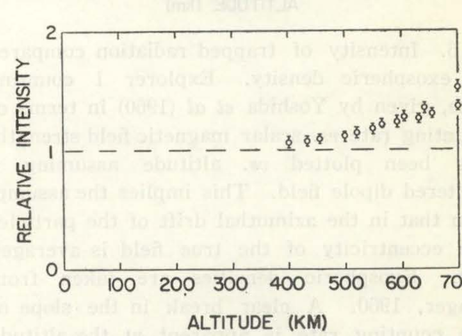

Fig. 5. Altitude dependence of intensity observed in Sputnik II (Vernov *et al*, 1958).

phere near this altitude and another component with a larger scale height takes over.

If only the atmosphere were to control the lifetime, and therefore the intensity, then the proton intensity should increase continually with altitude. In an earlier publication (Singer,[5] 1959) we estimated however that the adiabatic invariance of the magnetic moment should break down in a certain region where the magnetic field becomes too weak to contain the particles for long periods of time, essentially in the region where the radius of curvature of the particle becomes comparable to some scale length of the magnetic field. In the case of a pure dipole field this scale length is $r/3$ at a distance r from the dipole. In the presence of strong hydromagnetic waves the scale length becomes the wave length of the waves as assumed by Welch and Whitaker.[4] A more quantitative treatment can be given to these ideas. In the case of the pure dipole field we have shown that the critical energy above which non-adiabatic effects become important, decreases with increasing altitude approximately as r^{-4} (nonrelativistically). Wentzel and Dragt have treated the problem of hydromagnetic waves further and Dragt reduces a variation of critical energy as r^{-11}. However, Lenchek and Singer[1] (1962) have shown that the dependence may be much flatter and should *vary* with distance. Unfortunately it is quite difficult to decide between the possibilities by observations presently available.

The effect of energy loss in the atmosphere will be to *flatten* the energy spectrum and decrease the exponent by 1.5. The effect of nuclear interactions, as treated by Freden

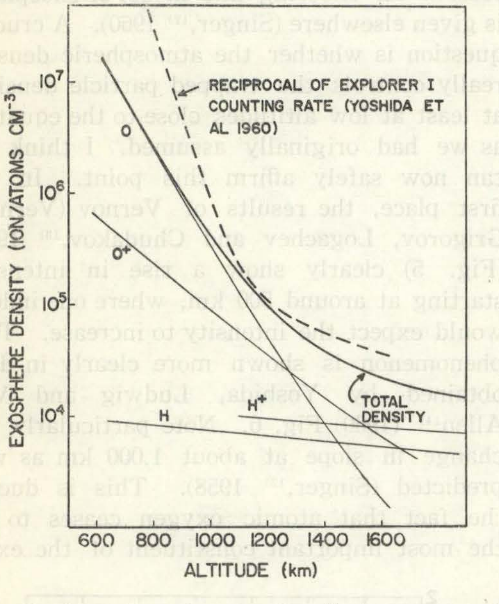

Fig. 6. Intensity of trapped radiation compared to exospheric density. Explorer I counting rate, given by Yoshida *et al* (1960) in terms of counting rate *vs.* scalar magnetic field strength, has been plotted *vs.* altitude assuming a centered dipole field. This implies the assumption that in the azimuthal drift of the particles the eccentricity of the true field is averaged out. Exospheric densities are taken from Singer, 1960. A clear break in the slope of the counting rate is apparent at the altitude where O^+ begins to dominate over neutral oxygen.

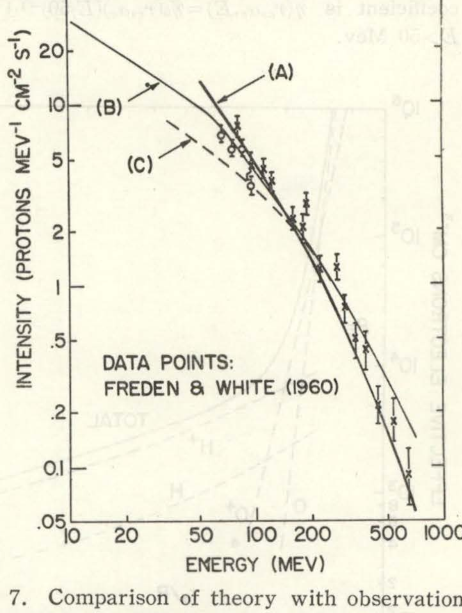

Fig. 7. Comparison of theory with observations. The data are from two integrating nuclear emulsion flights to ~1200 km with apogee on lines of force extending to ~1.3R geocentric (Freden and White, 1960). Curve A is the result of the present work, (E_c=1000 Mev) normalized to the data by dividing the computed intensity by 2.1. Curve B is the spectrum calculated on the basis of isotropic albedo with spectrum E^{-2} and including nuclear interactions (Freden and White, 1960). Curve C is the result of our numerical integration of the continuity equation for the same case.

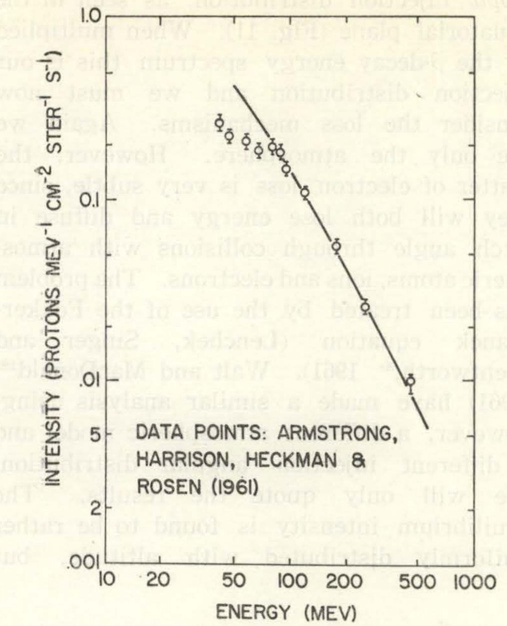

Fig. 8. Comparison with observations. Data are results of an integrating nuclear emulsion flight, apogee at ~1125 km, (maximum flux at ~1100 km, $r_e \sim 1.2R$) (Armstrong *et al*, 1961). Solid curve is result of the present work, normalized to the data, (E_c=1000 Mev) by dividing the computed intensity by 2.4.

and White[16] (1960), will be to *steepen* the energy spectrum by 0.5 at the very high energies, near 1 Bev. The combined effect gives a calculated energy spectrum which is in excellent accord with the observations (Figs. 7 and 8). The calculated spatial distribution (Fig. 9) also resembles the observations, although the presently available data are not adequate enough to make a detailed comparison.

The absolute intensities which are calculated from the neutron albedo theory turn out to be too high by a factor of 2 when compared to the observed intensity values of Freden and White[16] (1960) and Armstrong, Harrison, Heckman and Rosen[17] (1961). We consider the agreement, however, to be very satisfactory in view of the uncertainties in the albedo neutron spectrum and in the densities of the exosphere.

Trapped electrons

The β-decay of albedo neutrons gives rise to electrons with a spectrum having an end point of 782 kev. The largest quantity of

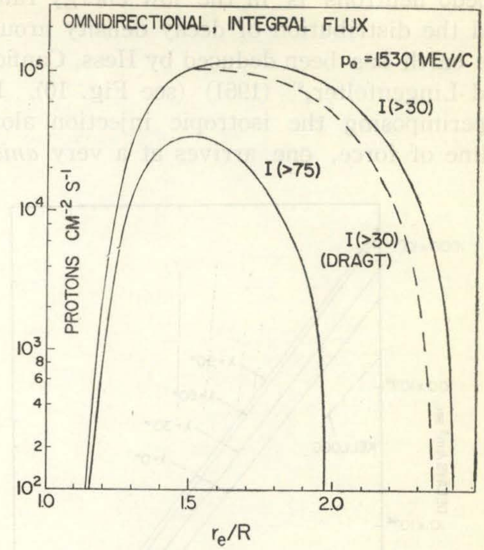

Fig. 9A. Omnidirectional, integral flux of trapped protons *vs.* altitude in the geomagnetic equatorial plane. We give results calculated for threshold energies of 30 and 75 Mev. The dashed curve is the altitude dependence computed by Dragt (1961). The similarity is fortuitous since Dragt has used a different albedo spectrum, E^{-2}, *vs.* the effective spectrum $E^{-2.9}$ used here.

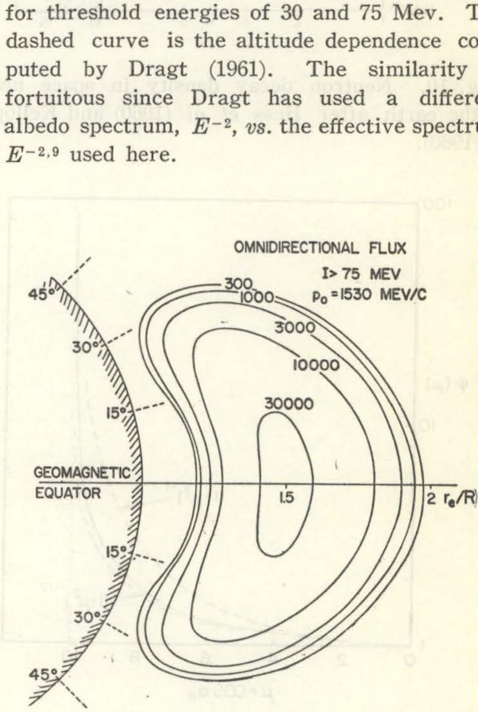

Fig. 9B. Omnidirectional intensity >75 Mev computed. The figures on the isointensity contours are in units of protons cm^{-2}s^{-1}. The upper limit to the spectrum is set by the breakdown of adiabatic invariance of the magnetic moment (Singer, 1959). The atmospheric density model assumes T=1500°K at 530 km (Singer, 1960).

albedo neutrons is in the low energy range and the distribution of decay density around the earth has been deduced by Hess, Canfield and Lingenfelter,[9] (1961) (see Fig. 10). By superimposing the isotropic injection along a line of force, one arrives at a very *anisotropic* injection distribution, as seen in the equatorial plane (Fig. 11). When multiplied by the β-decay energy spectrum this is our injection distribution and we must now consider the loss mechanisms. Again we use only the atmosphere. However, the matter of electron loss is very subtle, since they will both lose energy and diffuse in pitch angle through collisions with atmospheric atoms, ions and electrons. The problem has been treated by the use of the Fokker-Planck equation (Lenchek, Singer and Wentworth,[3] 1961). Walt and MacDonald[18] (1961) have made a similar analysis using, however, a different atmospheric model and a different injection angular distribution. We will only quote the results. The equilibrium intensity is found to be rather uniformly distributed with altitude, but

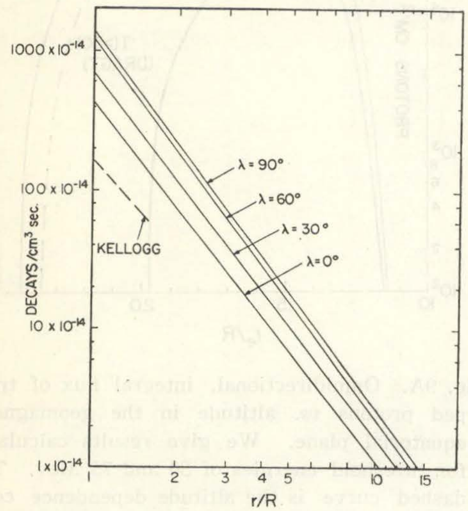

Fig. 10. Neutron decay density in space near the earth after Hess *et al* (1960) and Kellogg (1960).

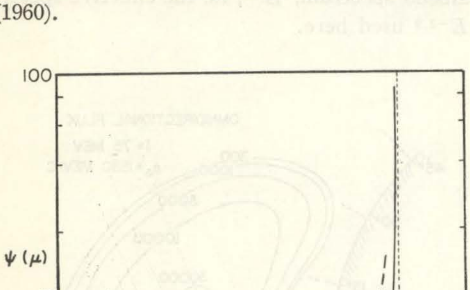

Fig. 11. Equatorial angular distribution of injected electrons, $\psi(\mu)$, calculated from a neutron decay density proportional to $r^{-2.7}$ (3-2 cos^2 λ), is shown by a solid line. We see that $\psi(\mu)$ can be approximated quite closely by 1/sin α_e. This distribution applies for equatorial altitudes $\gtrsim$3000 km. Below this level the distribution is$\sim$1/sin^2 α_e, assuming a decay density proportional to r^{-4}.

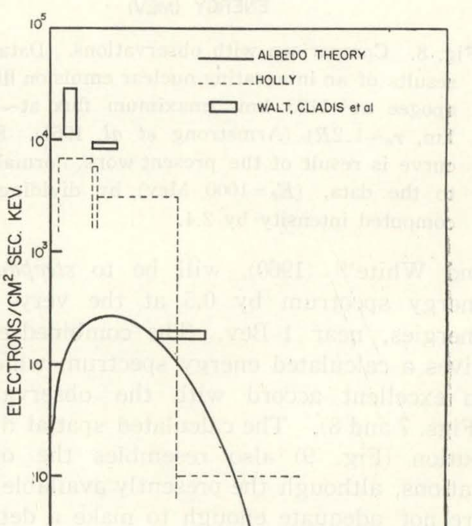

Fig. 12. Differential omnidirectional intensity of trapped electrons *vs*. energy. The solid curve is the result of the injection from neutron albedo, calculated for the case of pure energy loss. The curve is not normalized to the experimental data. It is calculated for an altitude of 1100 km on a line of force extending to 1.5R using an average effective density of 9.7×10^4 cm^{-3} computed from the exospheric model of Fig. 4. The dashed curve is the spectrum at 1100 km on the line of force extending to 1.5R (Holly *et al*, 1960). The data points (rectangles) are observations at$\sim$920 km on the line of force extending to$\sim$2.4R (Walt *et al*, 1960).

depends sensitively on the choice of atmospheric model. In particular, the density of the atmosphere at 2-4 earth radii is of great importance. The energy spectrum can be calculated less ambiguously, and our result is shown in Fig. 12, and compared there with available observations (Walt, Chase, Cladis, Imhof and Knecht,[19] 1960; Holly, Allen and Johnson,[20] 1961). It can be seen that the agreement is rather poor at low energies, but becomes increasingly better and may be quite good above 500 kev. The possibility exists, therefore, that the neutron albedo does indeed account for trapped electrons at energies greater than about 500 kev. A crucial question, however, concerns the existence of electrons of energy greater than the β-decay end point. For example, Vernov's group has reported the existence of 1.5 Mev electrons. These cannot be produced directly by neutron albedo although it is possible that neutron albedo may provide the injection mechanism and that the electrons are later locally accelerated.

However, for the bulk of the low energy electrons, the neutron albedo mechanism does not seem to be the correct explanation, and we must therefore assume that they are accelerated by an energy source which ultimately derives from the sun.

Acknowledgments

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