The 'Equilibrium' Anisotropy in the Flux of 10 MeV Solar Flare Particles and Their Convection in the Solar Wind

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CENTER FOR SPACE RESEARCH
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ABSTRACT

The Compton-Getting (convective) part of the equilibrium anisotropy in the flux of 10 MeV solar flare particles is calculated from particle spectra and solar wind speeds for seven events observed by the spacecraft Pioneer 6 and 7 in 1966. The convective part accounted for most of the anisotropy in every case, and in four cases appeared to be the entire anisotropy. This shows that convection is important and must be included in a realistic theory of the propagation of low-energy solar cosmic rays, although it can be neglected at higher energies. Scattering by hydromagnetic waves may also be important. Furthermore, since the diffusive part of the anisotropy was radial when it was not zero, the diffusion of these particles appears to be, at least locally, isotropic.

These conclusions depend on the facts that the convective part of the anisotropy is in the same direction as the solar wind, <u>not</u> perpendicular to the magnetic field, and that the correct formula for the Compton-Getting effect is $(2 + \alpha\gamma)\frac{V}{v}$.

The exponential decay time of these events at 10 MeV is calculated from the predominance of convection in the transport equation.

I. INTRODUCTION

McCracken, Rao and Bukata (1967a) and Rao, et al. (1967), hereafter referred to as MRB, have reported that during the late stages of seven solar cosmic-ray events observed in interplanetary space in 1966, the anisotropy in the flux of 10 MeV particles turned towards the sun-spacecraft direction and remained in that direction with a constant magnitude of the order of 10% for many hours in each event (see Table 1). MRB inferred that these radial anisotropies are a regular feature of the decay phase of solar particle events at 10 MeV, and this conclusion seems to be confirmed by further spacecraft observations with similar detectors (Allum, et al. 1968). MRB named these anisotropies the 'equilibrium' anisotropies, because they always occurred when the intensity was decreasing smoothly and "a smooth monotonic decreasing intensity against time curve is indicative of a distribution of cosmic radiation in diffusive equilibrium throughout the volume of the solar system accessible (magnetically) to the spacecraft" (MRB). They said the equilibrium anisotropy was the vector sum of two components: one from the $\underline{E} \times \underline{B}$ drift velocity of all the particles perpendicular to the garden-hose direction of the interplanetary magnetic field, and another component outward along the field lines due to the highly anisotropic diffusion of the particles away from the sun. This picture is illustrated in figure 1(a). In this picture, which is shown to be incorrect in the next section, the net anisotropy can be exactly in the radial direction only if its magnitude is given by the Compton-Getting (1935) effect for an "expulsion" velocity exactly equal to the solar wind speed. A smaller anisotropy would have to come from east of the sun-spacecraft line, and a larger anisotropy from the west. Since the equilibrium anisotropy was characteristically radial, and its magnitude indicated an expulsion velocity of the order of typical solar wind speeds, MRB concluded that it was the solar wind speed.

In view of this apparently strict relation between magnitude and direction it was decided to compare the magnitude of the equilibrium anisotropy with the magnitude according to the MRB model using the actual solar wind speed for each event.

Table I and figure 2 show that the equilibrium anisotropy did have the appropriate amplitude in four of MRB's seven events. On March 20, and July 11 the equilibrium anisotropy was larger than predicted, but on March 26 it was smaller. Assuming the gradient was radial, the March 20 and July 11 events could be explained in the MRB model by a temporary increase in the particle diffusion across field lines, allowing the diffusion part of the anisotropy to be more nearly in the radially outward direction. It is however, quite impossible to explain the small amplitude and yet radial direction of the equilibrium anisotropy on March 26 using the MRB model. We concluded from this event, and also on theoretical grounds discussed in Section II, that the MRB model is incorrect.

The correct picture of how the motion of the solar wind plasma (which produces the $\underline{E} \times \underline{B}$ drift in the MRB model) and the diffusion current add vectorially to produce the net particle anisotropy is shown in figure 1(b) and explained in the next section. On the basis of this model, the magnitude and direction of the equilibrium anisotropy indicates that it is mostly and sometimes entirely due to convection by the solar wind. This is exactly opposite to the case at higher energies where diffusion is more important. The rest of the equilibrium anisotropy is due to a diffusion current; when its magnitude is significant, as on March 20, 26,and July 11, its persistent radial direction indicates the diffusion is isotropic. This also is contrary to the situation at higher energies. Even the apparently outward density gradient during the March 26 event can be explained by convection.

The equilibrium anisotropy then is another striking example of how different the propagation of low-energy cosmic rays in the interplanetary medium is from the (reasonably well-understood) propagation of particles having energies of hundreds of MeV or greater.

We shall use the correct vector model and formula for the Compton-Getting (1935) effect and draw some preliminary conclusions about the role of convection by the solar wind on the propagation of those low-energy solar cosmic rays which have reached the equilibrium characterized by the equilibrium anisotropy.

II. THE DIRECTION AND MAGNITUDE OF THE CONVECTIVE ANISOTROPY.

The Archimedean spiral lines of the average interplanetary magnetic field $\underset{\sim}{B}$ move outward from the sun with the solar wind velocity $\underset{\sim}{V}$ (Parker, 1963). An observer in the spacecraft rest frame therefor sees an electric field $\underset{\sim}{E} = \frac{-1}{c} \underset{\sim}{V} \times \underset{\sim}{B}$, and this $\underset{\sim}{E}$ makes charged particles appear to drift in that frame with a velocity

$$V_{DRIFT(1)} = C \frac{\underset{\sim}{E} \times \underset{\sim}{B}}{|\underset{\sim}{B}|^2} = \underset{\sim}{V}_{\perp}$$

(Ahluwalia and Dessler, 1965).

However, the interplanetary field is not smooth and irregularities in the field scatter particles (Jokipii, 1966, Roeloff, 1965). Particles are scattered even if there is no gradient in particle density. These irregularities in the field are also carried outward from the sun by the solar wind, and they push the cosmic rays outward <u>along</u> the field lines with a velocity just

$$V_{DRIFT(2)} = \underset{\sim}{V}_{\parallel}$$

Thus the convection of the magnetic field and its irregularities in the solar wind makes the total convective drift velocity = $\underset{\sim}{V}_{\perp} + \underset{\sim}{V}_{\parallel} = \underset{\sim}{V}$, not just $\underset{\sim}{V}_{\perp}$, as MRB assumed. The convective velocity of the particles is the total solar wind velocity, as it is when the average magnetic field is zero (Gleeson and Axford, 1967). The average magnetic field $\underset{\sim}{B}$ only determines the direction and strength of the anisotropy in the diffusion tensor, and does not affect the convective part of the anisotropy in the particle flux.

The convective part of the flux anisotropy is always in the direction of motion of the solar wind, irrespective of the direction of the average magnetic field.

This result was derived more directly by Allis (1956) for hard-sphere scattering in a magnetic field, integrated over all particle energies. Klimas (1966) extended Allis' result to differential fluxes and "hot" scatterers by the differential moments method Gleeson and Axford (1967) used for the case of zero average magnetic field. Gleeson (1969) has also found that the convection term is in the direction $\underset{\sim}{V}$ and not $\underset{\sim}{V}_{\perp}$ in a strong magnetic field, but inadvertently (Gleeson, personal communication, 1969) dropped the $\underset{\sim}{V}_{\parallel}$ term in going from his equation 4.6 to 5.3 .

Including the parallel part of the convective anisotropy makes a substantial and qualitative difference in the interpretation of the equilibrium anisotropy since it removes the need for most of the outward diffusion current parallel to the magnetic field such as MRB show in their figure 21 (similar to figure 1a in this paper), to produce a radial anisotropy of the correct magnitude.

Following the notation of Axford and Gleeson (1967), the anisotropy of particles in a small energy range is

$$\underset{\sim}{\delta} = (2 + \alpha \gamma) \frac{\underset{\sim}{V}}{v} - \frac{3}{v} \frac{K \cdot \nabla U}{U} \qquad (1)$$

$$= \underset{\sim}{\delta}_c + \underset{\sim}{\delta}_d$$

where v = particle speed

U = the particle density per unit energy

$\alpha = (T + 2mc^2) / (T + mc^2)$

T = particle kinetic energy

γ = exponent of differential flux spectrum, $vU \propto T^{-\gamma}$

V = solar wind velocity

K = diffusion tensor

The first term in (1) is the Compton-Getting (1935; Gleeson and Axford, 1968; Forman, 1969) effect due to convection by the motion of the scatterers imbedded in the solar wind. The second term is due to diffusion through the scattering medium. Equation (1) is illustrated in figure 1b,c.

Solar wind speeds measured by the MIT Faraday cup plasma probe (Bridge and Lazarus, personal communication, 1967; Forman, 1968) on the same spacecraft during the equilibrium anisotropy events reported by MRB are given in table 1. The spectral indexes are MRB's estimates from their two-point spectra earlier in each event when the flux was larger. The University of Chicago experiment of the same spacecraft gives the same exponents within about 15% for every event (Pyle and Smith, personal communication, 1967). This uncertainty in γ hardly affects the application of equation (1) since real fluctuation in the solar wind speed during the events was usually larger. The Compton-Getting anisotropy calculated from the convective term in equation (1) with $\alpha = 2$ for these non-relativistic particles (7.5 to 45 MeV) is given in the table and compared with the observed anisotropies in figure 2. The diffusion term $\frac{-3K \nabla U}{vU}$ is the difference between the observed and convective anisotropies.

III. THE RELATIVE MAGNITUDE AND SIGN OF DIFFUSION AND CONVECTION IN THE EQUILIBRIUM ANISOTROPY.

Figure 2 also shows the observed and convective (Compton-Getting) anisotropy for galactic particles of the same energy (McCracken, *et al.*, 1967b). The radially outward convection of galactic particles is almost exactly cancelled by inward diffusion because of the outward density gradient (O'Gallagher, 1967, Jokipii and Coleman, 1968), the observed anisotropy is much smaller than the convective anisotropy.

In contrast, Table I and Fig. 2 show that the observed equilibrium anisotropy for solar flare particles is always of the order of the convective anisotropy and sometimes equal to it.

On Jan. 2, Jan. 19, March 25, and Sept. 28, diffusion was negligible compared to convection at the spacecraft since the entire observed anisotropy can be accounted for by the Compton-Getting (convective) anisotropy. During the other events, the diffusive anisotropy was not zero, but still smaller in magnitude than the convective anisotropy. This is clear evidence that the convective term in the flux, and hence in the transport equation for these particles, is <u>not negligible</u>. Since convection is neglected in the solar-flare particle propagation theories (Parker, 1963, Burlaga, 1967) which work very well at neutron monitor energies, these theories are unrealistic at low energies where the equilibrium anisotropy shows that convection usually dominates at ~1AU.

The equilibrium anisotropy on March 26 shows that these theories do fail at 10 MeV, and illustrates the gross effect of convection on the equilibrium spatial distribution of low energy particles. By equation (1), ∇U was <u>positive</u> on March 26, indicating the particle density at the spacecraft was <u>increasing</u> with distance from the sun. This cannot occur in the usual theories neglecting convection where the equilibrium particle density is found to decrease monotonically with distance from the sun.

Parker (1965) however, has shown that solutions of the transport equation including convection (but neglecting the energy-change terms, and assuming constant and isotropic diffusion coefficient) do have outward particle density gradients late in solar flare events if the parameter RV/K is large enough and the observation is not too close to the boundary. It is tempting to imagine that the boundary may have been farther away on March 26 than during the other events.

We can crudely estimate RV/K by taking

$R \sim 2AU = 3 \times 10^{13}$ cm

$K \sim 3 \times 10^{20}$ cm^2-sec^{-1} (Jokipii and Coleman (1968))

value for 10MeV galactic particles at solar minimum

$V \sim 4 \times 10^{7}$ cm-sec^{-1}

Then RV/K ~ 4. This is large enough to produce a substantial outward gradient at $\frac{r}{R} \sim 1/2 = 1AU$ (Parker, 1965). RV/K will vary from event to event if K does, but if the energy-dependence of K is at least as strong during solar events as it is for quiet times (Jokipii and Coleman, 1968), RV/K will be 20 times larger at 10 MeV than it is at 1 BeV. It is then possible for convection to be negligible at high energies but not at low energies during the same event.

The evidence that diffusion is negligible when the equilibrium anisotropy is observed implies an almost energy-independent exponential decay time for the particle flux.

The transport equation in a spherical solar wind is

$$\frac{\partial U}{\partial t} + \nabla\cdot\left(\underset{\sim}{V}\,U - K\cdot\nabla U\right) = \frac{2V}{3r}\frac{\partial}{\partial T}(\alpha T U)$$

Evidently, $K\nabla U \ll VU$ during the equilibrium anisotropy, so

$$\frac{\partial U}{\partial t} + \frac{2V}{r}U + V\frac{\partial U}{\partial r} \sim \frac{2V}{3r}\frac{\partial}{\partial T}(\alpha T U)$$

Now if $K\nabla U = \epsilon\,\frac{2+\alpha\gamma}{3}\,VU$

and ϵ is so small that even $\epsilon\frac{Vr}{K} \ll 1$,

$$\frac{\partial U}{\partial t} = -\frac{2V}{r}\left(U - \frac{1}{3}\frac{\partial}{\partial T}(\alpha T U)\right) = -\frac{2V}{3r}(2+\alpha\gamma)U$$

This gives a decay time of about 14 hours, which is typical for solar protons $\sim$ 10 MeV.

Note that this holds for particle energies at which the equilibrium anisotropy is observed, and so far this is only from 7.5 to 45 MeV, and with less certainty, from 45 to 90 MeV. Within this range, the decay time calculated above is only weakly dependent on particle energy (not proportional to 1/K which would be energy-dependent). This decay time will also be fairly uniform from event to event, as V and γ are pretty much the same from event to event.

The difference between the observed and convective anisotropies is so small on Jan. 2, Jan 19, March 25, and Sept. 28 that the "diffusion velocity" $-\frac{K \cdot \nabla U}{U}$ is certainly much less than the solar wind speed, and could be very much less. If the "diffusion velocity" is not much larger than $V_A{}^2/V$, where V_A is the Alfven speed, scattering by propagating hydromagnetic waves will be the important diffusion mechanism, and should be included in a complete transport theory for these particles (Parker, 1963; Klimas, 1966).

IV. THE DIRECTION OF THE DIFFUSION CURRENT IN THE EQUILIBRIUM ANISOTROPY.

It is apparent from figure 2 that the diffusion term was a significant fraction of the equilibrium anisotropy on March 20, March 26, and July 11. Nevertheless, the equilibrium anisotropy was still radial. Since the convection current is always radial (contrary to the model MRB used), the diffusion current <u>must have been radial</u> in each of these events where it can be measured. The magnetic field was not constantly radial during all of these events (Burlaga, personal communication, 1969), so the diffusion current was presumably in the direction of the particle density gradient, and unrelated to the direction of the field. This then implies that the diffusion was isotropic. This corroborates Jokipii and Parker's (1968) conclusion that low-energy solar cosmic rays are transported quite effectively across the mean direction of the interplanetary magnetic field. The total absence of "co-rotation" in the anisotropy of 10 MeV galactic cosmic rays (McCracken, *et al.*, 1968b) indicates that galactic particles also diffuse isotropically in the interplanetary medium.

V. CONCLUSIONS.

The convective part of the equilibrium anisotropy is in the radial direction, *not* perpendicular to the magnetic field. The convective part is calculated from the Compton-Getting effect and found to be larger than the diffusive part. From this we concluded that convection, and possibly scattering by propagating hydromagnetic waves, must be included in any realistic theory of the transport of low-energy cosmic rays away from the sun.

A reasonable value of the exponential decay time of the low-energy solar flare particle flux is derived by neglecting spatial gradients entirely. In this picture, the particle density is essentially uniform in the radial direction (while the equilibrium anisotropy is in progress) and the anisotropy and the time-dependence observed are due to convection and adiabatic deceleration in the expanding solar wind.

The values of $K \nabla U/U$ derived from the difference between observed and convective anisotropy are not very accurate, but are at least consistent with the qualitative effects of convection on the flare particle distribution in space discussed by Parker (1963) and Fisk and Axford (1968). The apparently positive (outward) gradient on March 26 can only be explained by convection.

The radial direction of the diffusive part of the anisotropy (on the three occasions when its magnitude was significant) indicates that these 10 MeV particles diffuse isotropically in the interplanetary medium where they are observed.

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Captions to figures

Figure 1 a) MRB model of convective and diffusive contributions to the equilibrium anisotropy.

b) corrected model

c) corrected model with isotropic diffusion

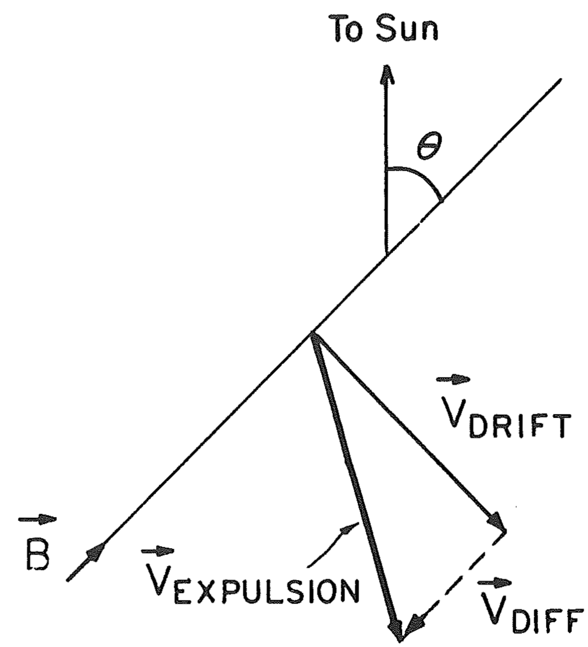
Figure 2 Comparison between observed and convective (Compton-Getting) anisotropy for the events in Table 1.

Caption to tables

Table 1. Equilibrium anisotropy events in fluxes of 10 MeV solar particles reported by McCracken, et. al. (1967a) and Rao, et al. (1969). Spectral indexes are for the isotropic part of the differential flux, $dj/dE \propto E^{-\gamma}$. Solar wind speeds were measured by the MIT plasma probe on the same spacecraft (Pioneers 6 and 7; Bridge and Lazarus, 1967). The convective (Compton-Getting) anisotropy is calculated from equation (1) in the text. Corresponding parameters for the anisotropy in the flux of galactic particles of the same energy are shown in the last row for comparison.

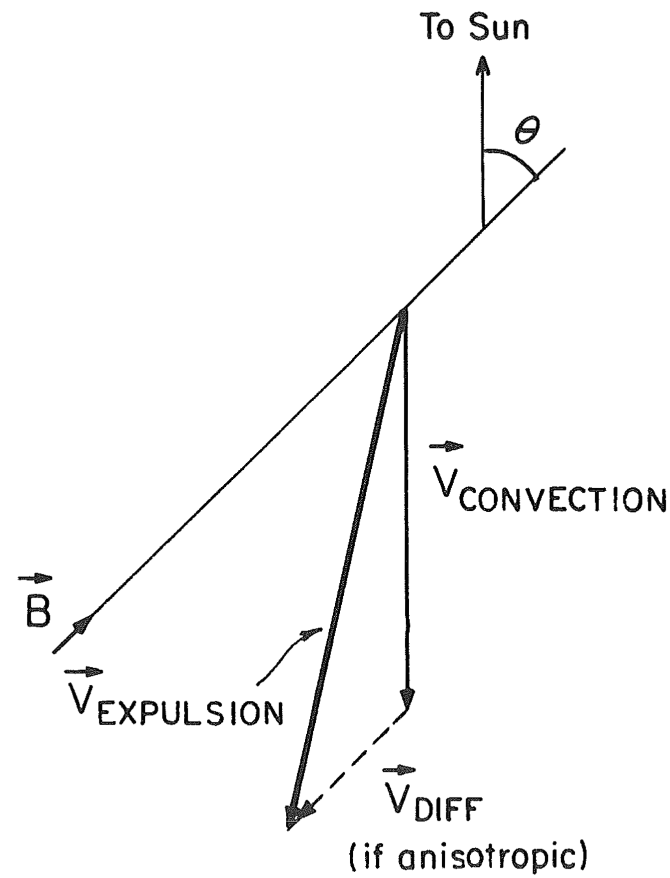
TABLE I

PERIOD, UT	OBSERVED EQUILIBRIUM ANISOTROPY, %	SPECTRAL INDEX γ	SOLAR-WIND km/sec	COMPTON-GETTING ANISOTROPY, % (Variation due to real variations in solar wind velocity.)	(implied) $\frac{K\nabla U}{U}$, cm^2/sec-AU
2 Jan. 1966 0700-2000	9.2	4.1	360-400	8.2 - 9.1	$< 2 \times 10^{20}$
19 Jan. 1966 1000-2000	9.3	4.4	350-375	8.4 - 9.0	$< 2 \times 10^{20}$
20 Mar. 1966 0600-1200	18.8	3.8	525-575	11.2 - 12.2	$(16 \pm 1) \times 10^{20}$
25 Mar. 1966 0100-2100	10.1	3	525-625	9.4 - 11.2	$< 2 \times 10^{20}$
26 Mar. 1966 to 27 Mar. 0900-0900	8.4	4	525-600	11.7 - 13.4	$(9 \pm 2) \times 10^{20}$ (positive)
11 July 1966	18.0	3.8	600-700	12.8 - 15.0	$(9 \pm 3) \times 10^{20}$
28 Sept. 1966-0700 to 1 Oct. 1966-2400	8.1	4.0	340-360	7.6 - 8.0	$< 1 \times 10^{20}$
7-45 MeV galactic particles	<0.2%	~ 0.6	~ 400	~ 3	$\sim 7 \times 10^{20}$ (positive)



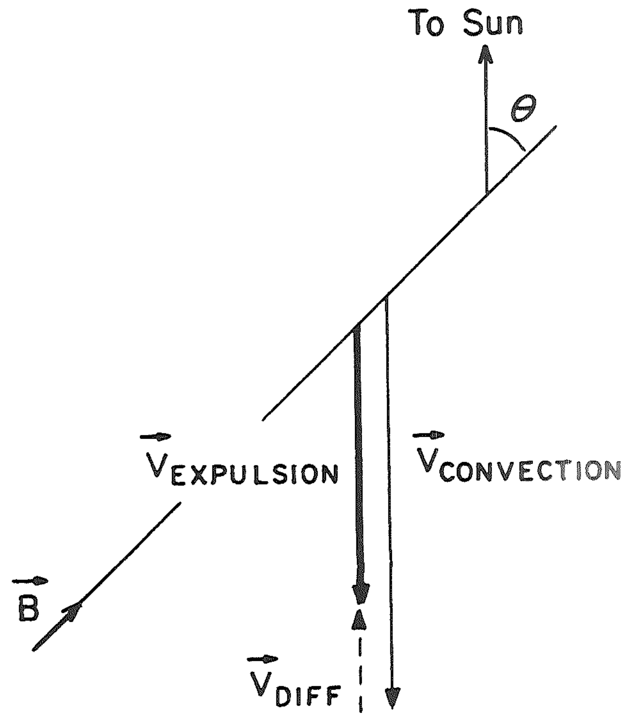
MRB MODEL

Fig. 1a



CORRECTED MODEL

Fig. 1b



CORRECTED MODEL WITH
ISOTROPIC DIFFUSION

Fig. 1c

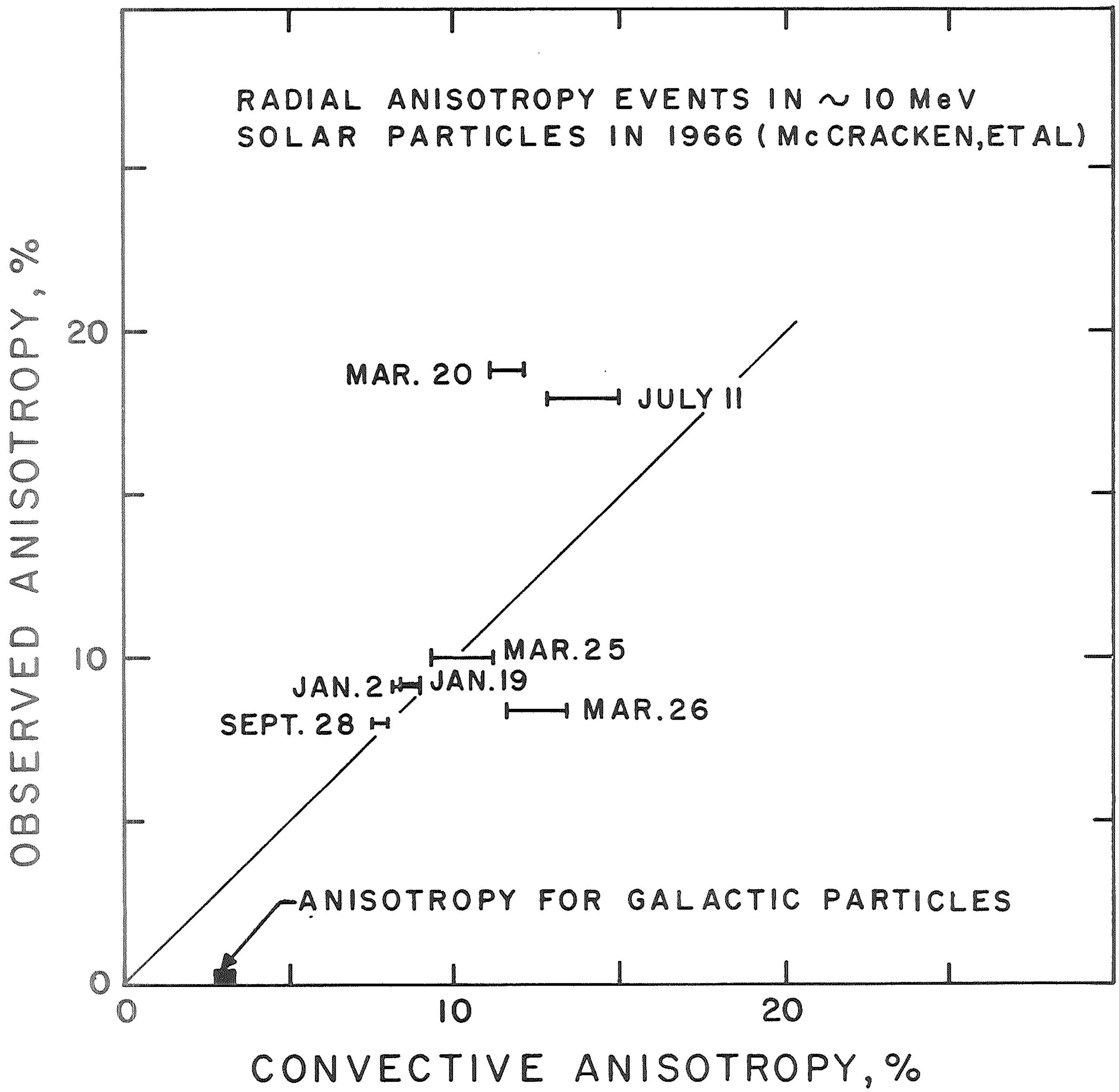

RADIAL ANISOTROPY EVENTS IN ~ 10 MeV SOLAR PARTICLES IN 1966 (McCRACKEN, ET AL)
OBSERVED ANISOTROPY, %
CONVECTIVE ANISOTROPY, %
0
10
20
MAR. 20
JULY 11
MAR. 25
JAN. 2
JAN. 19
MAR. 26
SEPT. 28
ANISOTROPY FOR GALACTIC PARTICLES

Fig. 2