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Original Investigations

Intensity and Energy Spectrum of Electrons Accelerated in the Earth's Bow Shock*

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Abstract. Shock waves accelerate charged particles in the solar atmosphere, in interplanetary space and around the Earth's magnetosphere. Acceleration of both electrons and protons occurs in the Earth's bow-shock. The acceleration of protons up to 100 keV appears to be a steady state process and may even occur upstream from the bow shock due to waves generated by reflected solar wind protons. The electrons, on the other hand, are known to be accelerated in or near the shock. The intensity of these electrons ranges from $\sim 10^2$ to 2×10^3 (sr cm^2 sec keV)$^{-1}$ at 14 keV. The energy spectrum is not a simple power low and is highly variable. If segments of the spectra are fitted to a power low, slopes ranging from —2 to —4.5 result over the energy range 0.5 to 100 keV.

Key words: Bow Shock — Acceleration of Protons and Electrons.

Acceleration of particles by shock waves in space is known to occur in a variety of astrophysical objects. Acceleration to relativistic energies evidently takes place in the blast wave generated by a supernova explosion. There are several lines of evidence to indicate that flare produced shock waves in the solar atmosphere accelerate particles. (These shock waves may also serve to trigger additional flares). The two strongest lines of evidence for charged particle acceleration by shock waves in the solar corona are the following:

1. It is widely accepted that type II solar radio noise emission arises from a disturbance (shock wave) travelling outward from a large solar flare (Wild *et al.*, 1963). It is often observed that such disturbances create type III (fast-drift) radio emission over a wide altitude range (Wild, 1969). The type III emission is believed to be due to electrons with velocities in the range 0.2 to 0.7 times the speed of light. The interpretation is that the shock wave (type II radio phenomenon) accelerates electrons. The electrons in turn move away from the shock along coronal magnetic field lines in

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* To Prof. G. Pfotzer in honor of his 65th birthday.

both directions. Thus, some of the type III radio bursts drift down in frequency (upward moving electrons) and others drift upward (downward moving electrons).

2. When solar flares are situated at large southern latitudes or at longitudes far removed from 60° W, most energetic flare particles reach the Earth only after a delay of several hours and then with a slow build-up of intensity. However, in a few cases of flares situated well beyond the cone of direct propagation to Earth, very rapid, short-lived particle increases have been noted (Anderson, 1969a). Following these increases the particle intensity gradually built up over a period of many hours. In these cases the flare caused strong type II radio wave emission showing that shock waves were present. The interpretation given to these observations (Anderson, 1969a) is that the shock wave spreads out in the solar atmosphere over tens of degrees of latitude and longitude accelerating particles as it does so. When the shock wave crosses those coronal field lines which extend to the vicinity of Earth, the particles accelerated there move readily to Earth. In the meantime the particles accelerated in the flare region are diffusing away from their acceleration site and gradually, after many hours, reach the field lines passing close to Earth in appreciable intensity. The shock waves are observed to travel at speeds about 1000 km/sec so that they require only about 8 minutes to move across 40° near the equator.

When these same shock waves leave the corona and travel through interplanetary space, they may accelerate solar particles already present there due to earlier flares (Lindgren, 1968; Singer and Montgomery, 1970; Palmeira *et al.*, 1971; Ogilvie and Arens, 1971). The observed particle increases last only about 15 minutes and are closely associated with the passage of the shock front. The intensity of protons of energy 0.3 to 3 MeV typically increases by a factor of 3 to 100. Since the solar particle spectrum is very steep, energy gains of only about a factor of 3 are needed to account for such increases. Two ideas for the observed energy gain have been suggested:

1. Axford and Reid (1963) suppose that acceleration occurs whenever interplanetary field lines connect the shock front and the Earth's bow shock. This mechanism gives the required energy gain. For example, consider protons with energy of 0.4 MeV. Their velocity is 8000 Km/sec, about 15 times greater than a typical shock velocity near Earth. For a proton with initial pitch angle $\sim 30°$ only 3 to 10 reflections from the moving shock front are required to double or triple the kinetic energy. The time that the necessary configuration of field lines must be maintained is on the order of 10^3 seconds. At times the interplanetary field is sufficiently quiet to meet this condition.

2. Fisk (1971) adopts a similar idea but replaces the bow shock by the irregularities that occur throughout the interplanetary field and result in

diffusion of solar particles. His theory gives sufficient acceleration provided that the diffusion coefficient for ~1 MeV protons is $\sim 10^{19}$ $\mathrm{cm}^2\ \mathrm{sec}^{-1}$. Since this is the value of diffusion coefficient implied by the observations of the equilibrium anisotropy, the theory must be regarded as having some observational basis.

Ogilvie and Arens give some observational examples which tend to support the Axford-Reid idea. However, Palmeira *et al.* (1971) have reported that shock associated increases of the short-lived variety occur large distances from Earth where it is not possible for the Axford-Reid mechanism to work.

Study of particles associated with a shock on 15 May 1972 led to some further conclusions about shock acceleration in interplanetary space:

1. The interplanetary magnetic field was not connected to the Earth's bow shock from as early as 30 minutes prior to the first appearance of the protons up to the time the shock passed over the spacecraft. It was concluded that the Axford-Reid mechanism was not at work on this occasion.
2. The acceleration mechanism that acts on protons in front of the shock also acts on electrons. However, the mechanism is energy dependent since electrons below ~20 keV were not affected.
3. Electrons were accelerated behind the shock. Fluxes of electrons in the energy range 0.5 to 2 keV were very great, but the fluxes then drop rapidly with energy and above ~25 keV few electrons were present. Evidently a separate and entirely different acceleration mechanism acts behind the shock. This mechanism may simply be the dissipation of the shock energy as it propagates through interplanetary space.

Particle acceleration in the Earth's bow shock has been extensively observed. Fan *et al.* (1964) reported transient increases of electrons of energy ~30 keV and higher in the position where the Earth's bow shock was expected to lie. It has since been confirmed that the largest fluxes of these electrons are encountered in or just behind the shock structure (Anderson, 1969b and references therein). These electrons travel along interplanetary field lines away from the shock where they are observed with decreasing intensity the greater the distance from the shock. It is quite certain that in the case of these electrons their acceleration mainly occurs in or near the shock and not in front of the shock. It is also clear that the acceleration of electrons above about 10 keV energy is not a steady state process. It appears that the dissipation of shock energy is not sufficiently great to produce a blanket of electrons that exists continuously just behind the shock. One the other hand the acceleration of protons in or upstream from the shock does appear to be a steady state process.

Asbridge, Bame and Strong (1968) reported that protons having energy several times the solar wind proton energy flow outward from the bow shock. The ion density is 1 to 10% of the incoming solar wind density

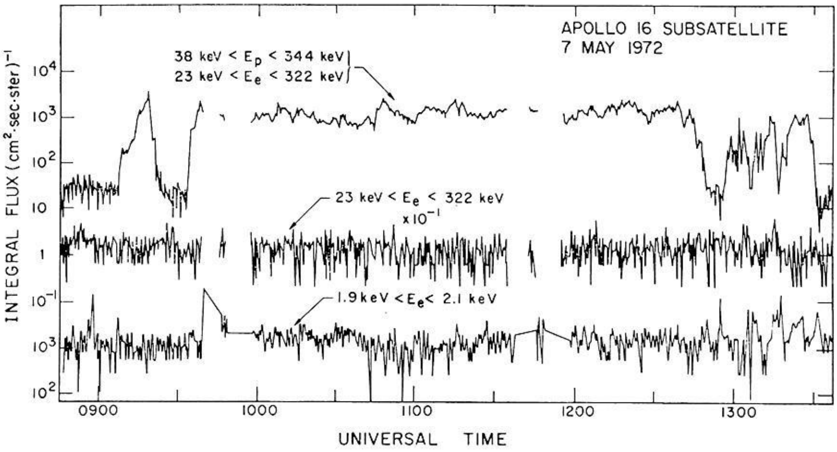

Fig. 1. Protons and electrons from the Earth's bow shock. The subsatellite is about 40 R_F from the bow shock to which it is convected by the interplanetary field lines during most of the observation shown in this figure. The switching on and off of the proton flux is due to the magnetic field lines making and breaking contact with the bow shock. The protons are accelerated in a steady state process

and their total energy density may become as high as 50% of the solar wind energy density. They conclude that part of the solar wind is accelerated and reflected upstream. The accelerated protons are not found inside the bow shock, in the magnetosheath. Scarf *et al.* (1970) report measurements on what is presumably this same population of particles. They refer to these proton fluxes in and outside the shock region as suprathermal protons. They find the proton fluxes are correlated with electrostatic waves at $f \sim 3$ KHz near the shock.

In at least one case the outward-flowing protons were associated with the presence of large amplitude hydromagnetic waves. Such waves have been known to be frequently present on interplanetary field lines connected to the bow shock (Heppner *et al.*, 1967; Greenstadt *et al.*, 1968; Fairfield, 1969; Russel *et al.*, 1971). Study of their properties leads to the conclusion that these waves are Alfvén waves which cannot travel upstream against the solar wind flow. Fairfield (1969) then suggested they must be locally produced upstream and that it is the outward flowing protons moving against the solar wind that generates these waves.

Protons of energy 30 to 100 keV are regularly found upstream in the solar wind on field lines that connect to the bow shock. They have been found (Lin *et al.*, 1974) to be present at least 90% of the time on such field lines. The acceleration of these protons is thus a steady state process just as is the energization and reflection of solar wind protons at lower energies. Furthermore, the flux level of these protons remains remarkably constant

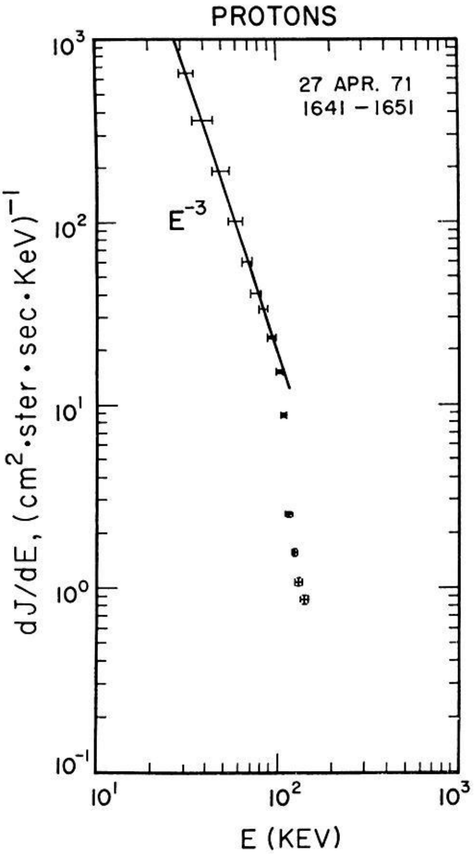

Fig. 2. Energy spectrum of bow shock protons. From 30 to 100 keV they have a power law spectrum, E^{-3}. Above 100 keV the proton intensity is sharply cut off

for many hours at this time (Fig. 1). This flux level changes from day to day but is in the range 100 to 1000 protons $(cm^2 \ sr \ sec \ keV)^{-1}$. The spectrum of these particles is closely fit by a power law and usually having form E^{-3} from 30 to 100 keV. Above 100 keV the spectrum is very sharply cut off (Fig. 2). This fact must be considered of great importance in diagnosing the mechanism which accelerates these particles. It should be emphasized that the appearance of these protons in front of the Earth's bow shock does not depend on the presence of solar flare particles or interplanetary shock waves. The sudden switching on or off of the proton flux as seen in Figure 1 is characteristic of satellite observations of these protons. The switching on is always interpreted as being due to the spacecraft encountering field lines which pass through the bow shock. The hypothesis is that such field lines always carry these protons.

The lower energy outward flowing protons and the 30 to 100 keV protons may be different parts of the same particle spectrum. That is, all the upstream protons from 30 keV to 100 keV may have been accelerated and ejected outward by the same process. One check that can be made of this possibility is to extrapolate the higher energy spectrum down to the energies measured by the Vela satellites. When this is done it is found the intensities at 3 keV would be 10^6 (cm^2 sec sr keV)$^{-1}$ in close agreement with the Vela measurements.

Three possible origins for the energetic upstream protons are:

1. They are accelerated in or near the bow shock, then travel large distances upstream without further energy change.
2. They are accelerated by a Fermi process using the bow shock itself as a stationary mirror and irregularities convected by the solar wind as the moving mirror.
3. They are accelerated throughout large regions of the upstream region but only on field lines connected to the bow shock.

The second possibility seems to be ruled out on grounds that the proton intensity changes very slowly as a function of distance along the IMF. The theory of acceleration in this manner predicts a rather rapid decrease in intensity with distance.

The apparent convection of the low and high energy protons suggests an origin in the bow shock (possibility 1). This is because the low energy electrons are clearly seen to be directed outward from the bow shock (the angular distribution of the 30 to 100 keV protons is not known).

However, there is evidence arguing against possibility 1. These arguments are given in Lin *et al.* (1974) and will not be repeated here. The situation must be said to be unresolved at the present time. If possibility 3 turns out to be correct, one would look for an interaction of the Alfvén waves, generated by the low energy protons, and those same protons which result in particle energy gain at the expense of wave energy. This possibility is not contradicted by the energetics of the situation: The energy densities in the solar wind, upstream waves and 30 to 100 keV protons are, respectively, 10^{-9}, 10^{-11} and 10^{-12} ergs/cm^3.

We now return to the question of electron acceleration in or near the bow shock. Figure 1 makes it clear that there is no steady state acceleration for electrons $\gtrsim 2$ keV as in the case for protons. No electrons at all can be detected above 23 keV: Their flux is at least 30 times less than the >30 keV proton flux. At times (near 1300 UT) there are weak fluxes of $\gtrsim 2$ keV electrons of intensity a few times 10^3 (cm^2 sr sec)$^{-1}$. It may be significant that in the example shown, these electrons appear at times when the spacecraft is being connected and disconnected several times per hour with the bow shock as evidenced by the switching on and off of the proton fluxes. This measurement was made far upstream in the solar wind on an inter-

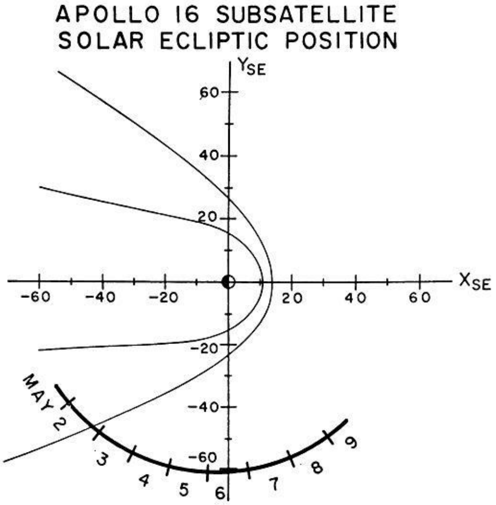

Fig. 3. Position of the Moon, and hence the Apollo 16 subsatellite, during the period of May, 1972 discussed in this article

planetary satellite and thus it alone does not conclusively rule out continual acceleration of electrons since these particles might be scattered or lose energy and not reach large distances from the shock. However, measurements made close to the shock also show that stable fluxes of protons often appear with no detectable, or else rapidly varying, electron fluxes.

Additional measurements of bow shock related electrons and protons have been made on the Apollo subsatellites, especially the one launched on the Apollo 16 mission. The subsatellite orbits the moon at low altitude (~100 km) so that in Fig. 3 only the path of the moon is needed to indicate the satellite's position with respect to the Earth's magnetosphere and bow shock. The subsatellite was in the magnetosheath until early morning on 2 May. Then for nearly a day it experienced many crossings by the bow shock as indicated by the on-board magnetometer (C. Russell, private communication). From the morning of 3 May on, the subsatellite was in interplanetary space and moved away from the bow shock although never more than about 40 R_E.

Some of the results from this study confirm earlier results and some are new:

1. Electrons of energy 2 to 100 keV are often present at or very near the position of the bow shock where the Moon crosses it on the down side of the Earth.

2. Protons of energy 30 to 100 keV appear just inside ($\lesssim$10,000 km) the shock and outside it.

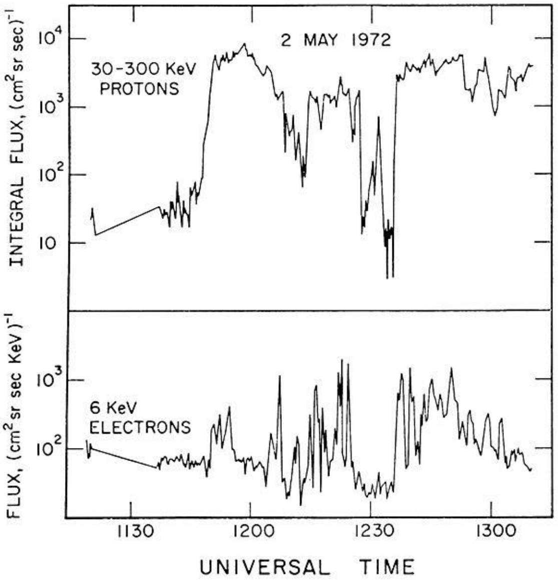

Fig. 4. Protons and electrons encountered just outside the bow shock. The electrons vary much more than do the protons

3. The electrons and protons are found upstream from the bow shock to distances along the field lines of at least 30 or 40 R_E.

4. The temporal appearance of the electrons is always spiky. The electron bursts last from a few seconds to a few minutes. They never switch on and remain quiescent for long periods of time as do the protons.

5. The appearance of the electrons is usually at the time the proton fluxes are being switched on and off rapidly (at times when the field line through the spacecraft is making and breaking connection with the bow shock). (Figs. 4 and 5 give further examples of this effect.

6. The electron intensities are highest near the bow shock but equally high intensities may be attained at distances up to ~40 R_E from the bow shock. There is, however, a tendency for the electron intensity to decrease with distance from the bow shock. The very great variation of electron intensity is in contrast to the nearly constant intensity level of the protons even when they are being switched on and off. Table 1 gives flux values at various electron energies for electron spikes located at different distances from the bow shock.

7. On a few occasions electron spikes, even of large intensity, may appear entirely in absence of protons. The event of orbit 104 in Table 1 is an example of this. A possible interpretation of this observation is that the field through the spacecraft is very rapidly connecting and disconnecting

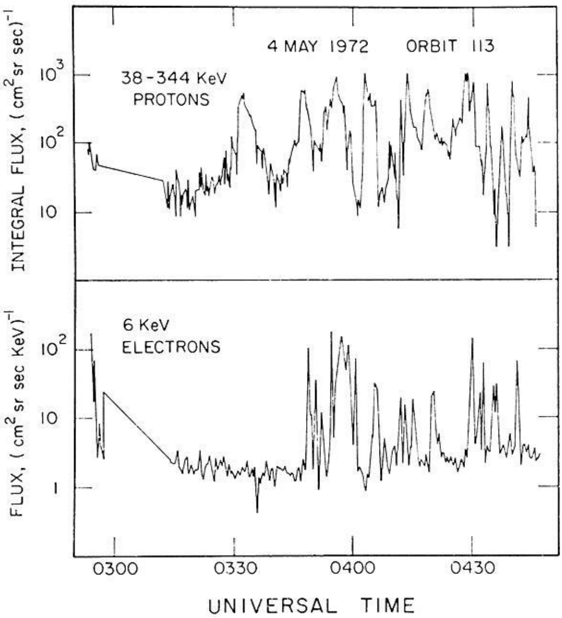

Fig. 5. This figure again shows the spiky character of the electrons. The absence of electrons before 0336 UT is due to the fact that the subsatellite is on the side of the Moon away from the bow shock. Protons from the bow shock can reach the detectors because their cyclotron radius is larger than the Moon's radius while the electron cyclotron radius is much smaller

Table 1. Fluxes of bow shock and upstream electrons. There is a tendency for the electron flux to decrease with distance from the bow shock but intense events may still be found for upstream

Time	2 May 0045 UT	2 May 1001 UT	3 May 1023 UT	7 May 1706 UT	9 May 1038 UT
Distance from bow shock	Inside $< 10{,}000$ km?	Close	Outside $\sim 30{,}000$ km	$\sim 2000{,}000$ km	$\sim 250{,}000$ km
Flux at energy of:					
0.5 keV	10^6	10^6	10^6	10^5	10^6
2	7×10^4	8×10^4	1.7×10^5	1.5×10^4	7×10^4
6	1.4×10^4	5×10^3	7.5×10^3	1×10^3	1.4×10^4
14	2×10^3	4×10^2	1×10^3	5×10^1	1.7×10^3
33	4×10^2	1	4	—	—

All fluxes in units of particles (sr cm^2 sec keV)$^{-1}$

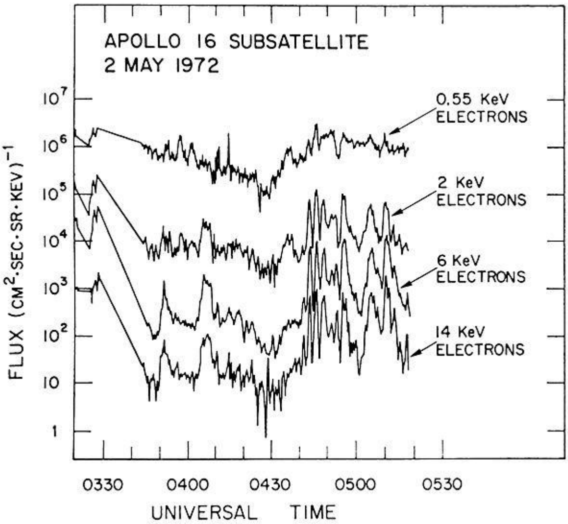

Fig. 6. Electron fluxes showing variations at a period of seconds. The satellite is probably just inside the bow shock at this time

with the bow shock. 100 keV protons require 15 seconds to travel 10 R_E while 50 keV electrons require only $\frac{1}{2}$ second. Thus if the field line remains connected for less than 15 seconds, protons cannot reach the spacecraft.

8. Electrons are rarely observed on the side of the Moon away from the bow shock. Of 24 orbits examined during the 2 to 9 May 1972 period, two orbits showed no bow shock electrons at all, 20 had substantially more bow shock electrons on the toward side while two showed more flux on the away side. This result shows that the electrons are moving away from the bow shock at distances of a few to 40 R_E from the bow shock. This result thus gives evidence that the electrons at least are accelerated in the bow shock or within short distances from it.

9. On two occasions, both while the subsatellite was close to the bow shock, the electrons were strongly modulated at a period of about 2.5 minutes. One of these occasions is shown in Figure 6. The electron intensities were unusually high as can be seen from the Table as well as Fig. 6. The energy spectrum during the largest peak is given in Fig. 7. The background is included in that Fig. 7. This background consists of solar wind electrons up to 1 or 2 keV, and on interplanetary particle spectrum of unknown (but presumably solar) at energies above these. Presumably this background constitutes the raw material for the bow shock acceleration process. If that is the case, the greatest relative enhancement of flux occurs above 10 keV and is quite small at 0.5 keV.

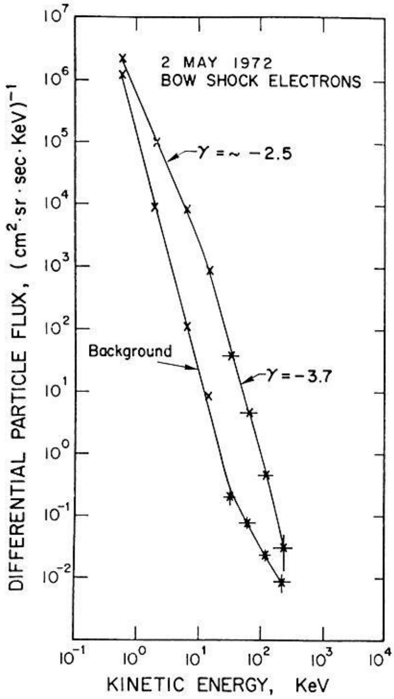

Fig. 7. Spectrum of electrons just behind the bow shock. The spectrum is not a simple power law

10. The spectral characteristics of the electrons are highly variable (Table 1). Overall, the spectra do not fit a power law with a single exponent. When segments of the spectra are fitted to power laws the exponents range from —2 to —4.5. The shape at higher energy sometimes is steeper (more negative) than at low energy. At other times the reverse is true.

11. The unusually high fluxes of electrons occurred when the subsatellite was behind the bow shock (C. Russell, private communication). It is likely that the subsatellite was very close to the bow shock at this time since it entered interplanetary space about 2 hours later. Thus we may have determined the electron intensity and spectrum in the acceleration region. However, only multiple satellites, such as the Mother and Daughter, can further explore the location of the acceleration region.

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