

50 years of research on particle acceleration in the heliosphere

L A Fisk

Department of Atmospheric, Oceanic and Space Sciences, University of Michigan
2455 Hayward St., Ann Arbor, MI 48109-2143 USA

Email: lafisk@umich.edu

Abstract. In 1965, and through the late 1960s, the heliosphere was considered to be a passive place, an impediment to the information on the galaxy contained in galactic cosmic ray observations, and on the Sun, from solar energetic particles. All this changed in the early 1970s with the discovery of the Anomalous Cosmic Rays (ACRs), and the subsequent acceptance that the ACRs are ionized interstellar neutral gas that is accelerated in the heliosphere by four orders of magnitude in energy. In the mid-1970s, *Pioneer* 10 & 11 observations provided direct evidence of acceleration. In 1977-78, diffusive shock acceleration was introduced, and subsequently developed in detail, providing compelling explanations for, e.g., the observed acceleration in co-rotating interaction regions, and a likely explanation for the acceleration of ACRs at the termination shock of the solar wind. In 2004 and 2008, the *Voyagers* crossed the termination shock, did not observe the acceleration of the ACRs, but did observe that low-energy particles, up to a few MeV/nucleon, had identical spectra downstream from the termination shock, a distribution function that is a power law in particle speed with a spectral index of -5. When *Voyager* 1 reached ~120 AU, where the high-energy ACRs are at peak intensity, the ACR spectrum is also a -5 spectrum. Moreover, observations of suprathermal tails in the solar wind in the inner solar system have a -5 spectrum, often peaking downstream, but not at shocks. These observations led to the development of a new acceleration mechanism, the pump acceleration mechanism of Fisk & Gloeckler, which can account for all the observed -5 spectra.

1. Introduction

This paper is written in the style of the talk at this conference: It presents the personal reflections and opinions of the author as to the highlights, major events and milestones in research on particle acceleration in the heliosphere during the last 50 years, i.e. starting in 1965. This is not an effort to present a comprehensive review of all pertinent or related topics, or to provide a comprehensive list of references. The author apologizes in advance to anyone who considers that their contribution to this subject is more important than the contributions cited. For readers who would like a more comprehensive and less personal review of particle acceleration in the heliosphere, the Space Science Series of the International Space Science Institute (ISSI) includes *Particle Acceleration in Cosmic Plasmas*, ed. by Balogh, Bykov, Lin, Raymond, and Scholer, which is also published in Space Science Reviews, 172, Issues 1-4, 2012.

2. The situation in 1965

In 1965, the major issue in energetic particle research in the heliosphere was not how particles are accelerated, but rather how they are decelerated. Parker [1] introduced what we refer to today as the



Parker transport equation, for the purpose of describing the modulation of galactic cosmic rays (GCRs):

$$\frac{\partial U}{\partial t} + \nabla \cdot (\mathbf{u}U) - \frac{1}{3} \nabla \cdot (\mathbf{u}) \frac{\partial}{\partial T} (\alpha TU) = \nabla \cdot (\tilde{\kappa} \cdot \nabla U). \quad (1)$$

Here, U is the differential number density; \mathbf{u} is the solar wind velocity; $\alpha = (T + 2T_o)/(T + T_o)$, with T particle kinetic energy and T_o particle rest energy; $\tilde{\kappa}$ is the diffusion tensor. Note the second term on the left, which describes the adiabatic deceleration that GCRs suffer while diffusing among magnetic irregularities in the solar wind, which is expanding as it flows radially outward. The adiabatic cooling is substantial, several hundred MeV/nucleon [2].

Gleeson and Axford [3] refined the derivation of equation (1), and introduced the Compton-Getting effect on the streaming, \mathbf{S} , of energetic particles:

$$\mathbf{S} = \mathbf{u}U - \frac{\mathbf{u}}{3} \frac{\partial}{\partial T} (\alpha TU) - \tilde{\kappa} \cdot \nabla U \equiv C\mathbf{u}U - \tilde{\kappa} \cdot \nabla U. \quad (2)$$

Here, C is the Compton-Getting coefficient. Equation (2) led to a simple approximate solution to the modulation equation (\mathbf{S} can be neglected) known as the force field approximation.

In general, then, the attitude toward the heliosphere in the late 1960s and early 1970s was that it was a passive place, an interference for the more important observations of GCRs and what they tell us about the galaxy, and solar energetic particles and what they tell us about the Sun.

3. The discovery of the anomalous component

The situation with regard to particle acceleration in the heliosphere changed dramatically with the discovery of Anomalous Cosmic Rays (ACRs) in the early 1970s, and the subsequent acceptance that this was interstellar neutral gas that is ionized and accelerated in the solar wind, by some four orders of magnitude, as proposed by Fisk et al. [4]. Now the heliosphere was no longer a passive place, but rather a prodigious accelerator of energetic particles.

In the early 1970s, a series of observations began to reveal an unusual component of the energetic particles. The Chicago group [5] noted that the helium flux in the energy range from 20 to 30 MeV/nucleon exceeded the proton flux, which although not terribly dramatic was at least puzzling. Then in rapid succession, the Max-Planck-Maryland group [6], observing at energies of 1-10 MeV/nucleon, and the Goddard group [7], observing above 10 MeV/nucleon, found something that was truly strange. Shown in figure 1 are the observations of Hovestadt et al. [6] and McDonald et al. [7]. The oxygen fluxes are very much higher than the carbon flux and the helium fluxes. Nitrogen was also enhanced, but at that time no other element was observed to be enhanced. This led, in the paper by McDonald et al. [7], to the label “anomalous component,” or now the more common usage of Anomalous Cosmic Rays, or ACRs.

GCR researchers live for discoveries like this. GCRs provide essential information on important objects and processes in the galaxy: supernovae being the classic example—the composition, particularly the isotopic composition, provides information about basic nucleosynthesis. So when ACRs were discovered, the assumption of GCR researchers was that an exotic object had been discovered. In fact, Hoyle and Clayton [8] had a theory for the origin of ACRs based on the composition of white dwarfs in binary star systems. They had a carbon and oxygen rich surface on the dwarf, nuclear burning of the carbon, acceleration in a nova shock and so on. This is the kind of theory that was a thrill to GCR researchers.

When a theory is developed, each contributor approaches the problem from their own background and perspective. I was working on modulation back then, and took one look at the ACR spectra and concluded that they cannot be GCRs. Mel Goldstein, Reuven Ramaty and I had just written a paper about the amount of adiabatic deceleration in the solar wind that is suffered by GCRs, and the energy

loss is considerable, several hundred MeV per nucleon, and moreover does not permit spectra as steep as the spectra in figure 1 to survive [2].

So one day in 1973, I was sitting in Reuven Ramaty's office at Goddard discussing, along with Ben-Zion Kozlovsky, the puzzle of the ACR observations. And we had one of those light bulb-goes-off conversations, where you all say – that must be it. We came up with the simple explanation for ACRs that they were interstellar neutral gas that flows into the solar system due to the motion of the Sun through the local interstellar medium; the neutral gas is then ionized by charge-exchange and photoionization, and then picked up by and accelerated in the solar wind to ACR energies.

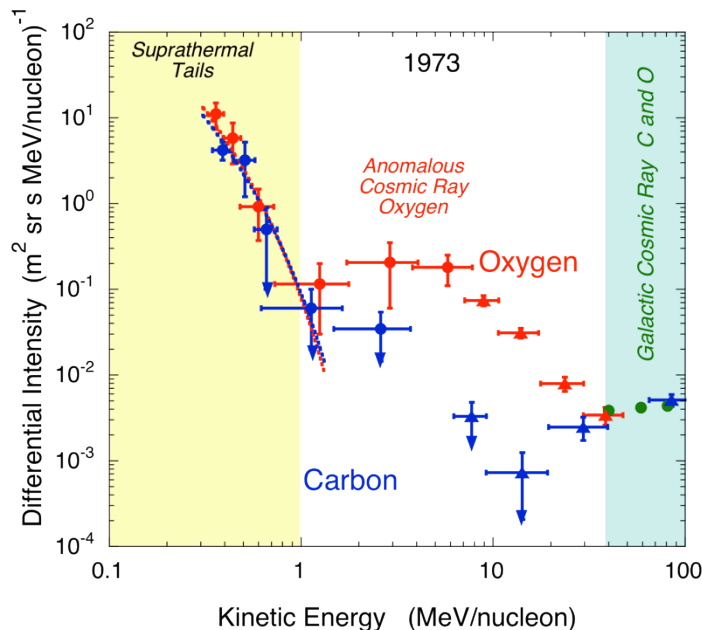


Figure 1. Differential intensity spectra of carbon (blue symbols) and oxygen (red symbols) measured by Hovestadt et al. [6] (filled circles) and McDonald et al. [7] (filled triangles). The oxygen spectrum has an extra component labeled “Anomalous Cosmic Rays” in the energy interval from about 1 to 30 MeV/nuc not seen in the carbon spectrum where only upper limits are shown.

The theory in Fisk et al. [4] provided a natural and easy explanation for ACRs. Interstellar neutral gas is expected to have exactly the correct composition. The elements enhanced in ACRs are all elements with high first ionization potential. They are hard to ionize and therefore are neutral in the interstellar medium and can readily penetrate into the heliosphere. The particles should be ionized only once in the heliosphere. Thus, they would be singly charged and therefore of quite high rigidity, and the concerns over modulation went away. We even predicted that elements like neon would be enhanced in ACRs, an enhancement that was subsequently observed.

I have always been grateful that my name started with ‘F’, as opposed to ‘K’ or ‘R’. The author list on the Fisk et al. [4] paper is alphabetical, but it is certainly one of the things for which I have been best known.

What the Fisk et al. [4] paper did not do is deal with how ACRs are accelerated. The paper simply said there must be a four-order of magnitude acceleration somewhere beyond the orbit of Earth. The interstellar ions were created primarily in the inner solar system, by photo ionization and charge acceleration, picked up by the solar wind thereby attaining energies of ~1 keV/nucleon, convected outward with the solar wind, and along the way somehow they were to be accelerated to ACR energies.

4. Research on particle acceleration begins to get traction

In the mid-1970s the topic of whether and how particles could be accelerated in the solar wind began to get traction. I was of course interested in the acceleration of ACRs, but this was also when the *Pioneers* were en route outward from Earth. McDonald et al. [9] published a paper comparing *Pioneer* 11 data with *IMP-8* data, and concluded that there was compelling evidence for extensive

interplanetary acceleration of low-energy particles. McDonald et al. attributed the acceleration to a basic Fermi mechanism, which Jokipii [10] had written about. In this mechanism particles are stochastically accelerated by interacting with randomly propagating Alfvén waves through a cyclotron resonance.

Barnes & Simpson [11] reported acceleration of energetic particles in the solar wind, also from *Pioneer* observations, and they identified co-rotating interaction regions (CIRs) as responsible, noting that the intensities peaked at the interfaces of the CIRs. They only speculated on possible acceleration mechanisms, noting that there were shocks at the interface, but also enhanced turbulence.

I also got in the act in 1976 with a stochastic acceleration mechanism built on transit-time damping, in which particles interact with magnitude fluctuations in the magnetic field through the Landau resonance [12]. This mechanism had an advantage over the cyclotron resonance mechanism cited by McDonald et al. [9] since a cyclotron resonance requires too much pitch angle scattering to be consistent with other observations. The Landau resonance with magnitude fluctuations in the magnetic field did not have that problem.

5. Diffusive shock acceleration

Everything changed again around 1978, with the full development of diffusive shock acceleration. I was working on other problems at the time, but it has always intrigued me that four separate researchers came up with essentially the same theory at the same time. The issue was not acceleration in the solar wind, but rather the acceleration of GCRs at shock waves generated by supernovae. Axford et al. [13] published their theory in the cosmic ray conference that year. Krymsky [14] published in the Soviet literature. Bell [15], and also Blandford and Ostriker [16] published a year later. I suppose the 1977 papers were first, but perhaps it was simply an idea whose time had come.

The concept was quite simple. Particles gain energy at a shock by repeatedly passing back and forth across the shock front, and each time they are compressed between the upstream and downstream magnetic irregularities, which are moving at different speeds, and the particles are accelerated.

The Axford et al. [13] presentation was particularly simple and insightful. If you write down the streaming equation (equation (2)), with the Compton Getting effect of Gleeson and Axford [3], and assume the streaming is continuous across the shock front, with upstream particles reflected off the incoming irregularities, and downstream being simply convected away, you find this simple relationship (for non-relativistic particles):

$$-\frac{u_{up}}{3} \frac{\partial}{\partial T}(2TU) = u_{ds} U - \frac{u_{ds}}{3} \frac{\partial}{\partial T}(2TU), \quad (3)$$

which is expressed in terms of the differential number density, U ; u_{up} and u_{ds} are the solar wind speed upstream and downstream of the shock front, respectively. Equation (3) is satisfied by a power law spectrum, $U \propto T^{-\beta}$, where the spectral index depends upon the compression ratio at the shock:

$$\beta = \frac{2(u_{us}/u_{ds}) + 1}{2(u_{us}/u_{ds}) - 2}. \quad (4)$$

It is straightforward to express these formulae in terms of differential intensity rather than differential number density.

The first formulation of diffusive shock acceleration, contained in the seminal four papers [13-16], has led an enormous body of theoretical research: papers on what happens when cosmic rays have enough energy to influence the incoming flow, cosmic ray mediated shocks. How are particles injected? How can shock acceleration be simulated numerically? And so on; research that continues to this day.

While all this detailed theory work was interesting, what diffusive shock acceleration did for acceleration in the solar wind was to provide a simple and straightforward explanation, one that could readily be understood, for a number of outstanding problems.

As examples, of which there are many, Marty Lee and I wrote a paper in 1981 on shock acceleration in CIRs [17], in which we included both the acceleration at the shocks surrounding the CIRs, as well as deceleration in the upstream solar wind. The model provided a good fit to contemporary observations, particularly at the higher energies, and offered a good explanation for the earlier discovery of acceleration in CIRs by Barnes and Simpson [11]. Pesses et al. [18] wrote a paper on a model that showed that a logical place to accelerate the ACRs was the termination shock of the solar wind. Marty Lee [19] wrote, what I always thought was one of his best papers, on coupling wave excitation and particle acceleration to explain acceleration at the Earth's bow shock. And of course there were countless applications of shock acceleration for propagating interplanetary shocks.

Despite the fact that diffusive shock acceleration had compelling underlying physics and a great deal of convincing theoretical work, nonetheless there were some nagging concerns that observational evidence was lacking that this was all that was happening. Not that diffusive shock acceleration was wrong, just that there was something missing. This was particularly true of propagating interplanetary shocks, which every time they were studied, the simple relationships, like the correlation between the spectral index and the compression ratio, or the expected spatial profile didn't quite fit (e.g., [20]). There was always a possible reason, e.g., time variations. We observe the consequences of the evolution of the shock, not just local conditions. The Earth's bow shock seemed to fit nicely with diffusive shock acceleration, but less so for propagating interplanetary shocks.

Then the *Voyagers* crossed the termination shock of the solar wind, which was the expected location of the acceleration of ACRs, up to 10-100 MeV, and it wasn't. *Voyager 1* crossed in December 2004 at 94 AU, and saw acceleration of particles up to a few MeV per nucleon, but the real ACRs showed no sign of being accelerated at the location of the *Voyager 1* crossing [21, 22]. *Voyager 2* crossed in August of 2007 at 83.7 AU, at a distance of more than 100 AU away from the *Voyager 1* crossing, and also showed only low-energy particle acceleration, with no evidence of the acceleration of the real high-energy ACRs [23, 24].

Of course there could be a reason. McComas and Schwardon [25] presented a model that argued that neither location where the *Voyagers* crossed was expected to accelerate high-energy particles, but rather the real ACRs should be accelerated on the flanks of the termination shock. However, again we are left with needing an excuse why diffusive shock acceleration did not do what had been the expectation for the acceleration of the ACRs for more than 25 years.

Then the *Voyagers* began to make what can be considered to be one of their most significant observations [26, 27]. As *Voyager 1* penetrated into the heliosheath the spectrum of the low-energy particles that were accelerated at the termination shock jumped around, but then locked onto a power law spectrum with spectral index of -1.5, when expressed as differential intensity, or -5 when expressed as a distribution function. The spectrum is a little steeper, but if you do the Compton Getting correction back into the frame of the solar wind, which is important for the lowest energy particles, it is a remarkably constant spectrum, with spectral index of -1.5 or -5 when expressed as a distribution function, for years. The same spectrum is observed from *Voyager 2*, which took longer to lock onto, but did lock onto a spectrum with a -1.5 spectral index. It appeared as if the termination shock at *Voyager 1* was traveling inward, and thus *Voyager 1* penetrated into the heliosheath faster. At *Voyager 2* the termination shock was not traveling inward and it took longer, but both still locked onto the same spectrum. Even more remarkable, the absolute magnitude of the intensity of these low-energy particles was the same at *Voyagers 1* and 2, even though the spacecraft were separated by a distance of more than 100 AU.

The particles accelerated at and downstream from the termination shock are not the real, high-energy ACRs. However, when *Voyager 1* finally reached the location where the ACRs actually peak, at ~120 AU, the spectrum of the real ACRs also has the same shape as the low-energy particles immediately downstream from the termination shock. As shown in figure 2, the spectrum is a power

law, expressed here as a distribution function, with spectral index of -5, and an exponential rollover at quite high energies.

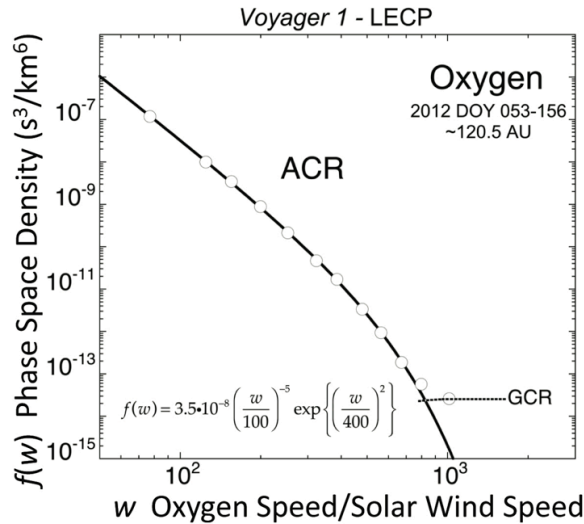


Figure 2. Phase space density of ACR oxygen as a function of oxygen speed/solar wind in the prime acceleration region at ~120 AU. The solar wind speed is taken to be 100 km/s. The data is from the LECP instrument on *Voyager 1* [28]. The equation shown in the figure is the formula for the common spectrum and provides an excellent fit to the observations (from [29]).

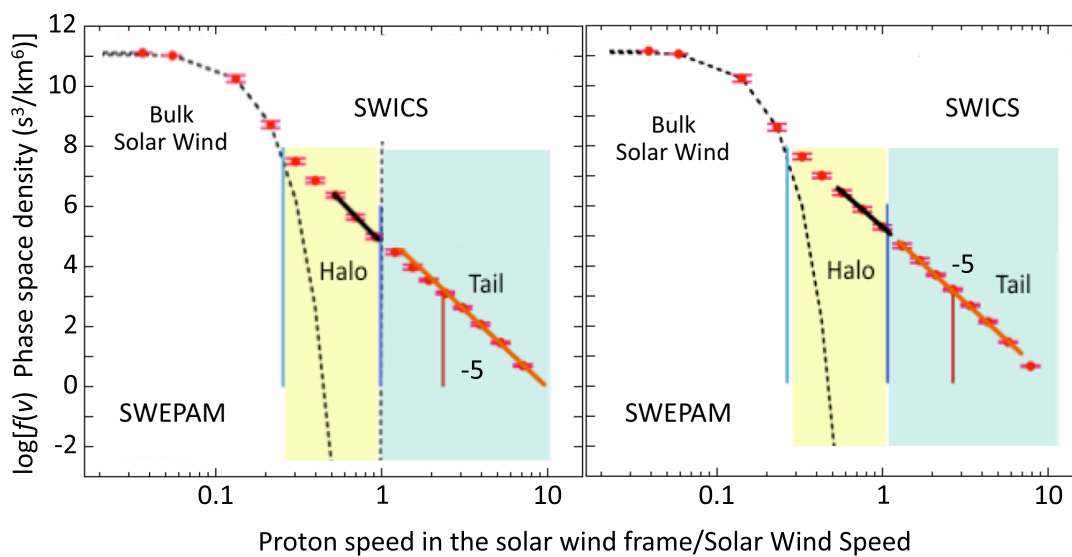


Figure 3. One-hour averaged solar wind frame velocity distribution functions showing the proton bulk solar wind, the halo and the tail segments during hour 11 of August 12, 2001, during which the strong (compression ratio of 3.85 ± 0.15) shock passed *ACE* (left panel) and during the hour of peak tail density that was observed one hour downstream of the shock (right panel) (from [29]).

The *Voyager* observations in the heliosheath caused George Gloeckler to ponder in great detail on the suprathermal tails of the solar wind that were being observed in the inner heliosphere by *Ulysses* and particularly by *ACE*. These are tricky observations, because at these low energies, up to 100 keV, the correction to transform into the frame of the solar wind must be done with great care. However, when the correction is done with care you discover that, almost without exception, every time you are in a region where particles are clearly being accelerated, i.e. the intensity is a local maximum, the spectrum, expressed as a distribution function, is also -5, with an exponential rollover.

As is illustrated in figure 3, these prime acceleration sites occur often, but not always, downstream from shocks, and what you actually see at the shock fronts are modulated spectra, as the particles

accelerated downstream propagate back to the shock front. It is no wonder that observations of particles accelerated at propagating shocks do not easily fit simple diffusive shock acceleration theory.

As much as you may think that diffusive shock acceleration is the answer to particle acceleration in the heliosphere, you should at least consider that these observations cannot be explained by diffusive shock acceleration. The acceleration does not occur at shocks, and there is no reason that diffusive shock acceleration will yield one particular spectral index, -5 .

6. The pump acceleration mechanism

Explaining these observations, spectra with a spectral index that is always -5 , for particles accelerated in vastly different conditions in the heliosphere—throughout the heliosheath and in the inner heliosphere—led George Gloeckler and me to develop the pump acceleration mechanism, which we have been publishing about for nine years now [29-35]. As with many new theories, our understanding of the theory and the derivations of the equations evolved over this period. However, from the beginning we knew that the physics of the pump acceleration was just as simple as is the physics of diffusive shock acceleration.

We note first that the -5 spectrum is most pronounced throughout the heliosheath and downstream from shocks in the inner heliosphere. Both are subsonic regions, with extensive compressive turbulence. Further, the regions where the -5 spectrum are most pronounced also have a ready source of particles to accelerate—pickup ions in the case of the heliosheath; the non-thermal distribution of solar wind particles heated crossing the shock in the case of interplanetary shocks in the inner heliosphere. Hence, we need to design an acceleration mechanism that works in the following situation:

- We have a volume of plasma, which is of fixed size, and which contains a population of particles that we are going to accelerate.
- The volume is thermally isolated, which means simply that there is no net inflow or outflow of the particles we want to accelerate, i.e., no large-scale spatial gradients.
- There is also a population of particles that contains the mass, in our case the solar wind, and an embedded magnetic field, and the solar wind and the embedded magnetic field are undergoing compressions and expansions, and are coupled to and cause compressions and expansions of the higher energy particles that we want to accelerate.

Since the volume of our plasma is constant, every compression region must be surrounded by an expansion region, and the compressions and expansions cannot do net work on the particles we want to accelerate. If no work is being done on the particles we want to accelerate, and we have a thermally isolated volume, the energy contained in the particles we want to accelerate must be constant. However, requiring that the total energy in the particles to be accelerated is constant does not restrict us from redistributing the energy from low to high energies through an irreversible process, which is what the pump acceleration does. The combination of cross-field diffusion out of compression regions into the surrounding expansion regions, and flow of particles and energy back into the source particle distribution, all with total energy conserved, is such an irreversible process that will redistribute particles, without changing their total energy, from the initial source population to higher energies.

And now the punch line: If you have a thermally isolated, constant volume system, containing an irreversible process, the system must tend to and achieve equilibrium when it achieves a state of maximum entropy. If you are in a state of maximum entropy and the compressions and expansions still continue, then each compression and expansion must be isentropic, which for an ideal gas requires that each compression and expansion must be adiabatic. If each compression and expansion is adiabatic, then the spectral index of the spectrum of accelerated particles must be -5 , as can be seen by considering the Parker transport equation for a compression and expansion with random velocity $\delta \mathbf{u}$ written in terms of a distribution function.

$$\frac{\partial f}{\partial t} + \delta \mathbf{u} \cdot \nabla f - \frac{\nabla \cdot \delta \mathbf{u}}{3} v \frac{\partial f}{\partial v} = 0. \quad (5)$$

In order for each compression and expansion to be isentropic, or adiabatic, the pressure, P , in particles that are being redistributed to higher energies must satisfy the adiabatic pressure equation, or,

$$\frac{\partial P}{\partial t} + \delta \mathbf{u} \cdot \nabla P + \frac{5}{3} (\nabla \cdot \delta \mathbf{u}) P = 0, \quad (6)$$

which can be achieved only if $f \propto v^{-5}$.

The concept that a -5 spectrum results when we require that energy is conserved in particles undergoing an irreversible process in compressions and expansions was first discovered by Andre Bykov [36] long before anyone worried about the -5 spectrum in the heliosphere. Bykov was doing a numerical calculation of particle acceleration in compressive turbulence in superbubbles in the interstellar medium, and when he applied a nonlinear constraint that the energy imparted to the accelerated particles fed back into the compressions and expansions, and thus energy was conserved in the system, he found a -5 spectrum. This was not noted at the time; the resulting spectrum plotted in Bykov [36] has a spectral index of -3. However, what was plotted was $v^2 f$, i.e., the resulting spectrum for f has a spectral index of -5.

The bottom line is that if you have: (1) a thermally isolated constant volume, containing compressions and expansions, and a low-energy particle population that you want to redistribute to high energies, conditions that, to a reasonable approximation, are readily available in the solar wind, and (2) an irreversible process in your volume, like spatial diffusion, the resulting particle population that gets redistributed to high energies will have a spectrum, expressed as a distribution function, with a spectral index of -5.

The pump acceleration mechanism has been developed beyond simply a concept. The governing equation that describes the time evolution of the distribution function, f_o , the most complete derivation of which is in Fisk & Gloeckler [29], is

$$\frac{\partial f_o}{\partial t} = \frac{1}{v^4} \frac{\partial}{\partial v} \left(\frac{\langle (\nabla \cdot \delta \mathbf{u})^2 \tau \rangle}{9} v \frac{\partial}{\partial v} (v^5 f_o) \right). \quad (7)$$

Here, τ is the characteristic escape time from a compression region, which is related to the cross-field diffusion coefficient. Equation (7) can be used to determine how rapidly and to what energy the -5 spectrum is established. Also, as might be expected, equation (7) can be used to demonstrate that the pump mechanism is a first-order and not a stochastic second-order acceleration, and thus fully competitive with diffusive shock acceleration.

There has been some confusion about Equation (7) [37]. The expression f_o is not defined as in a stochastic acceleration calculation, or, as you might observe, as the mean distribution function at a given energy. Rather, it is a distribution function that defines the mean pressure of the redistributed particles. Fisk & Gloeckler [29] show, however, that f_o , to any reasonable accuracy that you would care about, is what you observe.

Equation (7) has also been applied, with success, to all the problems we identified as needing an explanation. The curve on the full ACR spectrum observed by *Voyager 1* at ~120 AU that fits the data so well in figure 2 is the prediction of the pump acceleration mechanism. The pump acceleration mechanism also fully explains George Gloeckler's observations downstream from shocks in the inner heliosphere [29]. Finally, although our subject today is not interstellar physics, we even applied the pump acceleration mechanism to accelerate all galactic cosmic rays in the interstellar medium,

essentially Bykov on steroids, and got all the breaks in the spectrum in the right place, with the correct change in spectral index [34].

7. Concluding remarks

We have come a long way since 1965, when we had no indication that there was much acceleration in the heliosphere at all—to where we now have countless examples, and in some cases, like the ACRs, we have examples of acceleration to relatively high energies. Throughout, we have done what we do best in heliophysics. We have used the detailed observations available to us in the heliosphere to constraint and to understand the mechanisms responsible for the acceleration, and in doing so we serve the broader needs of astrophysics, since what we study can occur in other astrophysical settings. In my judgment the explanation of the ~ 5 spectrum, the pump acceleration mechanism, is yet another example of where we can demonstrate the value of heliospheric research to the broader astrophysical community, and we should do so.

Acknowledgments

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