The pump acceleration mechanism

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Abstract. Starting in the early 2000s, Fisk and Gloeckler developed a theory for a pump acceleration mechanism to account in detail for the ubiquitously observed, so-called, -5 spectra, a distribution function that is a power law in particle speed with spectral index of -5. To date, this theory has seen no general use in explaining data and relatively little constructive discussion. In this paper, we will make another attempt to interest experimentalists and theorists in using and expanding on the pump acceleration mechanism. The inevitability of the pump acceleration occurring in conditions that are common in space plasmas will be discussed, along with supporting numerical studies and observations.

1. Introduction
In the last decade, detailed observations have been made of the spectra of lower energy particles accelerated both in the inner heliosphere, from the Ulysses and ACE spacecraft, and in the heliosheath beyond the termination shock of the solar wind, from the Voyager spacecraft. In both cases, in specific events in the inner heliosphere, and throughout the heliosheath, the spectra are the same: a power law in particle speed with a spectral index of -5, when the spectrum is expressed as a distribution function (also referred to as phase space density); or equivalently, a differential intensity spectrum that is a power law in energy with a spectral index of -1.5. This common spectrum generally has an exponential rollover at higher energies, indicating the maximum energy particles acquire in the acceleration process.

To explain the common spectrum, Fisk and Gloeckler [1-6] developed a new acceleration mechanism, a pump acceleration mechanism. However, despite the fact that the pump acceleration mechanism can account for the common spectrum in all the different circumstances where it is observed, the theory has seen no general use, other than the applications of Fisk and Gloeckler, and relatively little constructive discussion. In this paper we will make one more attempt to interest experimentalists and theorists in using and expanding on the pump acceleration mechanism.

We provide a step-by-step, concise presentation of the logic behind the pump acceleration mechanism; we then discuss examples of where it is successful; and ways in which we can test the pump acceleration mechanism. All the arguments and conclusions summarized in this paper, as well as supporting observational evidence, are discussed in detail in Fisk and Gloeckler [5,6].

2. The theory of the pump acceleration mechanism
The following sections describe the essential features of the pump acceleration mechanism.
2.1. *The plasma conditions in which the pump acceleration mechanism operates*

The following are the plasma conditions in which the pump acceleration mechanism is expected to operate and accelerate particles:

- The plasma contains an embedded mean magnetic field. The energy in the particles is greater than that of the magnetic field, which has as its only function to couple the motion of the particles.
- The plasma can be considered to be in a fixed volume—i.e. on applicable scales we are not concerned with the expansion of the solar wind—and is thermally isolated, which means simply that there is no net influx or outflow of particles and energy across the boundaries of the volume; i.e., no large-scale spatial gradients.
- The plasma contains mesoscale compression and expansion regions. These compressions and expansions occur normal to the mean magnetic field, and the regions are of size large compared to the gyroradii of the particles that are to be accelerated in the plasma, but small compared to the total volume of the plasma.

*The pump acceleration mechanism should apply in very common conditions in the solar wind. In particular, the required conditions are likely to occur downstream from shocks, which are subsonic regions with ample compressions and expansions.*

2.2. *The proper description of particle behavior in the pump acceleration mechanism*

The particles to be accelerated have sufficiently high speeds so that they can spatially diffuse, which we define as: in the presence of a sufficient spatial gradient, they can escape from a compression region within the time that a compression region will become an expansion region. Recall each location is the site of alternating compression and expansion regions.

The compression and expansion regions have a cross section much larger than the particle gyroradii, and so the best description of the behavior of the particles within each compression and expansion region is the Parker [7] transport equation, written in terms of the distribution function, \( f \):

\[
\frac{\partial f}{\partial t} + \mathbf{u} \cdot \nabla f = \frac{V \cdot \mathbf{u}}{3} \frac{\partial f}{\partial v} + \nabla \cdot (\kappa \nabla f). \tag{1}
\]

Here, \( v \) is particle speed; \( t \) is time; \( \mathbf{u} \) is the mean velocity of the plasma, and is responsible for the compressions and expansions thru the term \( \nabla \cdot \mathbf{u} \); the spatial diffusion tensor is \( \kappa \).

*The particle behavior in the pump acceleration mechanism can be described by the Parker transport equation, which is the standard equation that has been used successfully to describe galactic cosmic ray modulation for over 50 years, i.e., we treat each compression and expansion region as a small modulation region.*

2.3. *The consequences for using the Parker equation for the total particle energy*

Particles gain or lose energy in the Parker transport equation only by an adiabatic compression or expansion; e.g. the adiabatic cooling of galactic cosmic rays in the expanding solar wind. In an adiabatic compression or expansion, no energy is added to or removed from the particles; no work is done on or by the particles. All that happens is there is a change in the volume experienced by the particles. Since the total volume is constant, the compressions and expansions do not result in a net change in the total energy of all the particles in our plasma.

*In the pump acceleration mechanism, the sum of the energy of the particles that are being compressed or expanded, plus the energy of the particles that are responsible for the compression or expansion, is constant.*
2.4. Why a high-energy tail develops and the spectrum of the tail
We have a thermally isolated system in which particles gain or lose energy by adiabatic compressions
and expansions. Total particle energy and number of particles are constants. We have an irreversible
process, the spatial diffusion. Under these circumstances, the system will evolve to a state of
maximum entropy, and in doing so will create a high-energy tail.

In a state of maximum entropy, the high-energy tail must be isentropic in each compression and
expansion region, or equivalently, the pressure in the high-energy tail must behave according to the
pressure equation for an adiabatic compression or expansion. Thus, the pressure, \( P_t \), in the tail between
particle speeds \( v_1 \) and \( v_2 \) must satisfy
\[
\frac{\partial P_t}{\partial t} + \mathbf{u} \cdot \nabla P_t + \frac{5}{3} (\mathbf{V} \cdot \mathbf{u}) P_t = 0 .
\]  

(2)

We can find the spectral form of the high-energy tail that satisfies equation (2) by first noting that
in a fully developed high-energy tail, spatial gradients between adjacent compression and expansion
regions are small, and thus there is no loss or gain of particles by spatial diffusion, in which case, from
equation (1), the particle behavior is described by
\[
\frac{\partial f}{\partial t} + \mathbf{u} \cdot \nabla f - \frac{\mathbf{V} \cdot \mathbf{u}}{3} \frac{\partial f}{\partial v} = 0 .
\]  

(3)

We can then integrate equation (3) over particle speed to determine an equation for the particle
pressure, and note that if \( f = f' v^{-5} \), where \( f' \) is a normalization constant, the resulting pressure
equation is equation (2).

\[
\frac{4 \pi m}{3} \int_{v_1}^{v_2} \frac{v^4}{v} \left[ \frac{\partial (f v^{-5})}{\partial t} + \mathbf{u} \cdot \nabla (f v^{-5}) - \frac{\mathbf{V} \cdot \mathbf{u}}{3} \frac{\partial f}{\partial v} \right] dv' = 0
\]

(4)

\[
\frac{\partial P_t}{\partial t} + \mathbf{u} \cdot \nabla P_t + \frac{5}{3} (\mathbf{V} \cdot \mathbf{u}) P_t = 0
\]

We can then integrate equation (3) over particle speed to determine an equation for the particle
pressure, and note that if \( f = f' v^{-5} \), where \( f' \) is a normalization constant, the resulting pressure
equation is equation (2).

2.5. The source of the energy that creates the high-energy tail
In our system, particle energy is conserved. There is no change in the sum of the energy of the
particles that are being compressed or expanded, plus the energy of the particles that are responsible
for the compression or expansion. It follows therefore that the energy that creates the high-energy tail
comes from lower energy particles.

The consequence of the conservation of energy was illustrated by Bykov [8], who modeled the time
evolution of the spectra of particles accelerated in super bubbles. The resulting nonrelativistic spectra
are shown in the left panel of figure 1, taken from Bykov [8]. The acceleration is due to mesoscale
turbulence generated by shocks. There is a nonlinear coupling between the accelerated particles and
the turbulence, such that the energy in the total system is conserved. Noting that \( v^2 f \) is plotted, the
time asymptotic spectrum (#5) is a power law with spectral index of -5.
In the pump acceleration mechanism, total particle energy is a constant, in which case the energy that creates the high-energy tail must come from the lower energy particles that are responsible for the compressions and expansions. Moreover, the Bykov [8] model confirms the conclusion that a system with mesoscale compressions and expansions, in which energy is conserved and there is an irreversible coupling between particles of different energies, results in a distribution function with a tail that is a power law with spectral index of -5.

2.6. The time evolution of the high-energy tail

Fisk and Gloeckler [5,6] carefully derived an equation that describes the time evolution of the spectrum of particles accelerated by the pump acceleration mechanism. The derivation is in terms of a nonstandard form for the mean distribution function, $f_o$, which is defined as the distribution function that determines the mean pressure in the accelerated particles, or

$$
\langle P \rangle = \frac{4\pi m}{3} \int v^4 f_o dv = \int P_v dv.
$$

This choice for the mean distribution function allows Fisk and Gloeckler to correctly capture the collective behavior of the particles within a compression or expansion region. The resulting acceleration that describes the time evolution of $f_o$ is then

$$
\frac{\partial f_o}{\partial t} = \frac{1}{v^5} \frac{\partial}{\partial v} \left( \frac{\delta u^2}{9\kappa} \frac{\partial}{\partial v} \left( v^5 f_o \right) \right).
$$

Here, $\delta u^2$ is the mean squared variation in the mean plasma speed and $\kappa$ is the spatial diffusion coefficient for diffusion across the mean magnetic field.

A typical solution to equation (6) is

$$
f_o \propto v^{-5} \exp \left[ -9\kappa/((1 + \alpha)^2 \delta u^2 t) \right].
$$

In this case, the diffusion coefficient is particle speed times a power law in particle rigidity, with spectral index of $\alpha$. The solution evolves into a power law with spectral index of -5 and an exponential rollover that increases with time.
Technically, \( f_o \) is not the observed mean distribution function. What is observed is the time average of the distribution function at a given particle speed, not an integral over particle speed, as in equation (5). However, Fisk and Gloeckler [5,6] show that in the -5 portion of the spectrum, \( f_o \) is identical to the time-averaged distribution function, and there are only small deviations between \( f_o \) and the time-averaged distribution function in the roll-over region of the spectrum.

The time evolution of the spectrum in the pump acceleration mechanism is well described by equation (6) and the resulting solutions, e.g. equation (7), and these solutions provide excellent fits to spectra observed in the many instances where the pump acceleration mechanism is expected to apply.

2.7. The rate of acceleration of the high-energy tail
We can determine the rate of acceleration in the pump mechanism by rewriting equation (6) in terms of the differential pressure, \( P_v \), in equation (5):

\[
\frac{\partial P_v}{\partial t} = \frac{\partial}{\partial v} \left( \frac{\delta u^2 v^2}{9 \kappa} \frac{\partial P_v}{\partial v} \right) + \frac{\partial}{\partial v} \left( \frac{\delta u^2 v}{9 \kappa} P_v \right).
\]

(8)

The first term on the right in equation (8) describes the diffusion of particle energy to higher energies. The second term describes a first-order acceleration.

The pump acceleration mechanism is a first-order acceleration, which will always accelerate particles more rapidly than any stochastic acceleration mechanism, and there are many cases where this first-order acceleration is comparable to or exceeds the first-order acceleration in diffusive shock acceleration.

2.8. Conclusions about the theory for the pump acceleration mechanism
If you have a plasma with the following conditions, which you can find in many locations in the solar wind:

1. The plasma is in a fixed volume that can reasonably be considered to be thermally isolated, with no net influx or outflow of particles and particle energy across the boundaries of the volume.
2. The plasma contains mesoscale compression and expansion regions, where the compressions and expansions are normal to the mean magnetic field that causes all particles within a region to experience either a compression or expansion.
3. There are particles with sufficiently high speeds, and thus sufficiently large gyroradii that they can spatially diffuse out of a compression region, into an adjacent expansion region, thereby irreversibly coupling the compression and expansion regions.
4. The tail will develop rapidly because the pump acceleration mechanism responsible for the high-energy tail is a first-order acceleration.

Then, a high-energy tail, a power law with a spectral index of -5, will develop.

3. Applications of the pump acceleration mechanism
The following are some particularly compelling applications of the pump acceleration mechanism.

3.1. The heliosheath
The heliosheath is an ideal location for the pump acceleration mechanism. It is a subsonic region, with dominant pressure in the interstellar pickup ions, and ample mesoscale compression and expansion regions.

Indeed, when Voyager 1 and Voyager 2 crossed the termination shock of the solar wind, each, after some initial fluctuations in the spectra, locked onto the differential intensity spectra shown in figure 2,
a power law with spectral index of -1.5, which is equivalent to a distribution function in particle speed, with spectral index of -5, the spectrum produced by the pump acceleration mechanism. Of even more importance, when Voyager 1 reached ~120 AU it observed the full ACR spectrum shown in figure 3, a distribution function that is a power law with spectral index of -5, extending up to 10s of MeV/nucleon in energy.

Figure 2. Voyager LECP observations taken from Decker et al. [12]; Gloeckler et al. [13].

As is discussed in detail in Fisk and Gloeckler [9], the acceleration of the ACRs in the heliosheath must be due to the pump acceleration mechanism, and cannot be due to diffusive shock acceleration at the termination shock. The pressure in the ACRs in the heliosheath is observed to be about half the total particle pressure in the heliosheath [10]. If ACRs originate at the termination shock on the flanks, as suggested by McComas and Schwadron (e.g., [11]), the ACR pressure would be added to the pressure in the pickup ions that are convected radially downstream from the termination shock with the solar wind. Pressure would then not be constant, as is required in the subsonic heliosheath, unless the pickup ion pressure could be reduced, which seems highly unlikely. Rather, it is necessary to accelerate the ACRs out of the pickup ions using the pump acceleration mechanism, which yields the correct spectral shape for the accelerated ACRs.

3.2. The interstellar medium
Superbubbles in the interstellar medium are also a possible location for application of the pump acceleration mechanism; the problem that Bykov [8] considered. There is ample energy in low-energy particles and supernovae to excite mesoscale compression and expansion regions.

Fisk and Gloeckler [14] applied the pump acceleration mechanism to the acceleration of all GCRs in the interstellar medium. The scale sizes of the turbulence were chosen realistically; particles were assumed to diffuse across the magnetic field by field line random walk; and the problem was done relativistically. The resulting spectrum is shown in figure 4. The slope below the knee, which occurs when the particle gyroradii equals the scale size of the turbulence, is fixed by the choice of parameters. The slope above the knee is a fixed multiple of the slope below the knee and agrees well with observations.
3.3. The solar wind at 1 AU
The pump acceleration mechanism is also important at 1 AU, and yields suprathermal tails with spectral index of -5. The acceleration frequently occurs in the subsonic regions immediately downstream of shocks, although it can also occur in the absence of shocks. Shown in figure 5 are typical observations at 1 AU. The observed spectrum has three distinct parts: The thermal solar wind, labeled the core in figure 5; a steep extension on the core labeled the halo; and finally the classic -5 tail, which given the small scale sizes at 1 AU only extends up to ~4 times the solar wind speed, where the spectrum rolls over.

Fisk and Gloeckler [6] developed a detailed theory for the halo portion of the spectrum, referred to as ‘the inefficient pump mechanism’. Particles in this speed range are unable to readily escape from a compression region and will experience a smaller than average compression and gain less energy. As a result the halo has a steeper spectrum, which Fisk and Gloeckler [6] demonstrate varies with the rigidity dependence of the diffusion coefficient.

Figure 5. A typical spectrum of particles that are accelerated in the solar wind at 1 AU. The core, thermal solar wind is shown in blue, the steep halo in red, and the common spectrum, with spectral index of -5 and an exponential rollover, in green.
There is a wealth of information available on particle acceleration from observations at 1 AU, which allows us to determine the dominant particle acceleration mechanism operating in the various solar wind plasma conditions. In the case of the pump acceleration mechanism, observations such as in figure 5 can, from the halo, reveal the required rigidity dependence of the diffusion coefficient, and from the particle speed at the roll-over of the spectrum, the rate at which particles are accelerated and/or the escape of the particles from the prime acceleration site. Comparison of the requirements of the pump acceleration mechanism with concurrent plasma and magnetic field measurements provide a full test of the pump acceleration mechanism. It must be emphasized, however, that very high time resolution measurements at all relevant particle energies are required to completely test every aspect of the pump mechanism. The scale sizes involved in acceleration at 1 AU are very small, compression regions with dimensions only a few times larger than the gyroradii of the particles being accelerated.

4. Concluding remarks
The acceleration mechanism of choice for particle acceleration in the solar wind has, for decades, been diffusive shock acceleration, which has been employed to explain acceleration to high energies at shocks associated with CMEs in the solar corona; acceleration at shocks at 1 AU; at CIRs; at planetary bow shocks, etc. In principle, the pump acceleration mechanism, which as with diffusive shock acceleration is first order, could be the dominant acceleration mechanism in many of these observed acceleration events. As we learn more about the pump acceleration mechanism, and in particular we verify all aspects of the pump mechanism with observations at 1 AU, we should expand our thinking and explore whether the pump acceleration mechanism is dominant over diffusive shock acceleration in some or even many of the events where particles are accelerated in the solar corona and the solar wind.

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