ACCELERATION OF HEAVY IONS IN THE SOLAR WIND

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Abstract. Several recent studies of the preferential acceleration and heating of solar wind heavy ions by the resonant cyclotron interaction are reviewed. It is concluded that this interaction is incapable of producing the observed differential speeds for reasonable solar wind parameters.

Heavy ions in the solar wind are often observed to have undergone preferential heating and acceleration relative to protons. At 1 AU, the heavy ions are seen to flow faster than protons and to have comparable thermal speeds, the temperatures tending to be proportional to the ion mass. These preferential effects are positively correlated to the value of the solar wind speed. The differential speeds of the ions, $\Delta v_{ip} \equiv |\vec{v}_i - \vec{v}_p|$, are also correlated with the local Alfven speed. Helios measurements of alpha particles showed that, closer to the sun, the differential speed was often equal to the Alfven speed, even though the Alfven speed increased substantially in the inner solar system. At these times, the kinetic energy flux of the alpha particles amounted to almost one-third of the kinetic energy flux of the solar wind as a whole, and it is important to understand how so much energy is concentrated into this so-called "minor" component.

The close connection between the differential speeds and the local Alfven speed suggests that the responsible mechanism is a wave-particle interaction. One such mechanism which would favor the energization of low charge-per-mass particles is the resonant cyclotron interaction. Since the Solar Wind Four Conference in 1978, several workers have been investigating the quasilinear resonant cyclotron interaction between parallel-propagating waves and solar wind ions, and this work will be reviewed here.

A parameter study of quasilinear effects of left-polarized (Alfven and ion-cyclotron) waves on test populations of heavy ions was produced by Dusenbery and Hollweg (1981). They found that the resonant interaction is capable of accelerating heavy ions from speeds less than the proton speed to speeds greater than the proton speed. They also found indications that the resonant interaction could produce mass-proportional heating. However, they also found that the dispersion relation for ion-cyclotron waves in an electron-proton plasma resulted in a critical value of $\Delta v_{ip}/V_A$ above which the heavy ions were no longer in resonance with the waves. This implies an upper limit to the differential speed which is locally obtainable from the resonant interaction. For He^{++}, this limiting value is only 0.2 V_A. This point was also discussed by McKenzie and Marsch (1982).

Dusenbery and Hollweg also estimated that approximately 20% of the total wave energy near the sun would be required to accelerate the solar wind concentration of He^{++} to the Alfven speed at 0.3 AU, as observed. The problem here is that the bulk of the solar wind wave energy is seen at low frequencies and the wave power declines with increasing frequency as $P \sim \omega^{-\gamma}$ where typically $1.5 \lesssim \gamma$

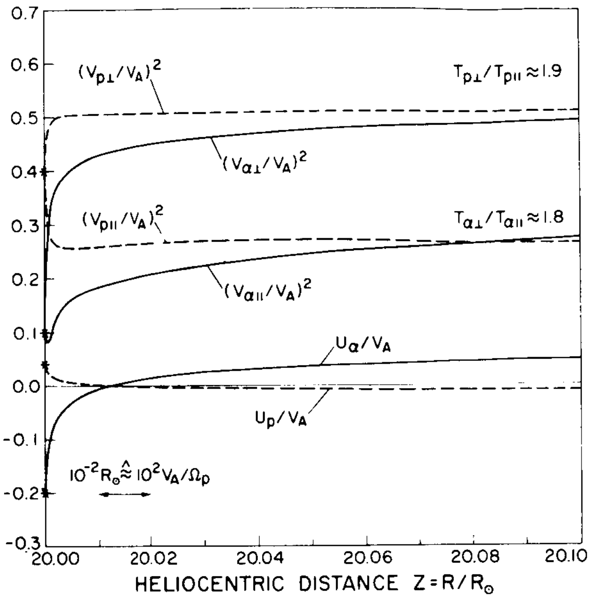


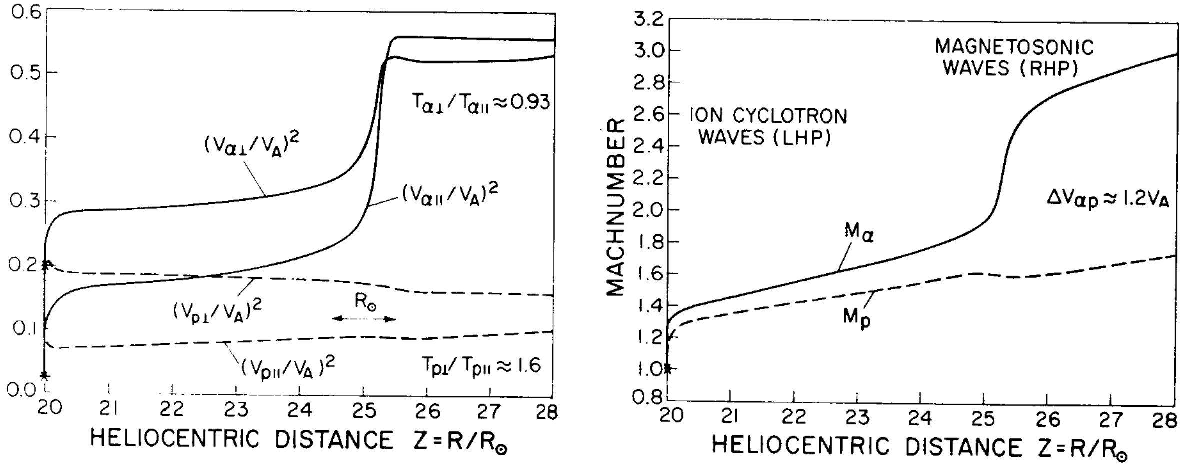
Figure 1. Calculated proton and alpha speeds relative to their center of mass frame and squared thermal speeds, all normalized to the local Alfven speed (after Marsch et al., 1982).

$\lesssim$ 2.0. The energy in the high-frequency, resonant regime which is available to the cyclotron interaction is several orders of magnitude too low.

This work, however, was a calculation of the local energization of test heavy ions, and as such, it did not consider two important points. Firstly, a spectrum of waves which can cyclotron resonate with heavy ions will also interact with the solar wind protons. One must study this simultaneous interaction and determine the extent to which the heavy ions are accelerated and heated in excess of the protons. Secondly, results of this local calculation must still be incorporated into a solar wind model to determine the evolution of the heavy ion populations under the continuous action of the resonant process allowing for the ongoing adjustment of the model parameters (such as the Alfven speed and the wave power) in the expanding solar wind, as well as for the effects of other participating forces. In particular, a local upper limit of $\Delta v_{ip}/V_A$ is not necessarily significant when V_A is decreasing: a process which could produce $\Delta v_{ip} = V_A/3$ at 0.1 AU might result in $\Delta v_{ip} = V_A$ at 0.3 AU if the actual particle speeds do not change.

The first work to deal with these questions was Marsch et al. (1982). They considered a system containing bi-Maxwellian distributions of protons and alpha particles and an initial power-law spectrum of parallel-propagating waves. Starting the calculation at 20 solar radii ($\cong$ 0.1 AU), they investigated the self-consistent interaction, following the evolution of the wave spectra, as well as the velocities and temperatures of the particles. They included the effects of the shifting model parameters as a function of radius, but did not consider any non-resonant forces except those produced by a radial magnetic field on a plasma with a double-adiabatic equation of state.

Their first result was that, as expected from the work of Dusenbery and Hollweg, the observed wave power levels in the resonant frequency range were too small to produce any significant effects. To continue the investigation, the wave levels were increased. Figure 1 shows an example of the normalized velocities and squared thermal speeds which result. The strong preferential heating and acceleration of alpha particles is obvious, and it is clear that the cyclotron resonant interaction can accelerate alpha particles through the proton speed. Note, however, that the total scale only extends over 0.1 R_s (R_s = solar radius). In this model, the wave effects proceed very quickly, energizing the particles within $10^{-2} R_s$. The wave energy, self-consistently calculated, is essentially depleted by this time and further energization takes place on the much slower convective scale as the expanding solar wind and decreasing field magnitude cause a rescaling of the resonant parameters. It would be interesting to follow this model system further to investigate this slower energization, but this evolution is obscured by another aspect of this model.



(a) (b)

Figure 2. As in Figure 1, except that the speeds shown in (b) are shown with respect to the inertial frame, $M_i \equiv v_i/V_A$ (after Marsch et al., 1982).

The resonant interaction which produced the results in Figure 1 took place with left-polarized ion-cyclotron waves. Marsch et al. have also included the effects of a resonant cyclotron interaction with an equally intense spectrum of right-polarized magnetosonic waves. This is motivated by the observation that $T_{\alpha\parallel} > T_{\alpha\perp}$ in the fast solar wind, which could be a signature of fast-mode heating. It is also suggested that this interaction could explain why $\Delta v_{\alpha p}$ is limited to the Alfven speed. According to this model, the energization by the ion-cyclotron waves, along with the decreasing phase speed in the expanding solar wind, allows the alpha particle distribution to move into resonance with the right-polarized waves, and this interaction completes the acceleration to $\Delta v_{\alpha p} = V_A$. In the example shown in Figure 2, this has all occured within six R_s. It is certainly plausible that, once the alpha particles have attained differential speeds comparable to the Alfven speed, an interaction with magnetosonic waves could produce parallel heating and prevent $\Delta v_{\alpha p}/V_A$ from increasing further as V_A declines. However, it is hard to see how the fast mode is itself responsible for the acceleration up to $\Delta v_{\alpha p} = V_A$. In order for an alpha particle to cyclotron resonate with the right-polarized mode, it must be travelling along the field at more than twice the Alfven speed with respect to the bulk plasma. Thus, only the high-velocity tail of the distribution will be able to interact with these waves. For the case shown in Figure 2, less than 5.7×10^{-4} of the alpha particles have this necessary speed at 25 R_s, where the model energization by the magnetosonic mode has already started. It is difficult to see how this enormous acceleration and heating of the entire distribution from an interaction with a tiny fraction of the particles can be other than a numerical artifact of the model.

Another model which deals with some of these questions from a different point of view has been presented by Isenberg and Hollweg (1983). This work does not include as detailed a picture of the microscopic interaction as Marsch et al., but it incorporates a reasonable simulation of the interaction into a full solar wind model which includes all other forces of interest. The central point of this model is that the energy problem is dealt with by invoking a "saturation and cascade" scenario. The authors assume that large-amplitude Alfven waves in the solar wind saturate when $<\delta \underset{\sim}{B}^2>/B_o^2 = \frac{1}{2}$, where $<\delta \underset{\sim}{B}^2>$ is the total magnetic variance (integrated over the entire spectrum). It is then hypothesized that the energy lost from the waves cascades to resonant frequencies where it is picked up by the particles through the resonant cyclotron interaction. The details of these nonlinear processes were not specified, as their physics is not well understood, but it was pointed out that this scenario is plausible and consistent with observations.

To incorporate this scenario into a solar wind model, one needs information on the propagation and dissipation properties of the waves in a multi-ion differentially flowing plasma. Unfortunately, at present, the only available theory of this type is restricted to Alfven waves in a thermally isotropic plasma (Isenberg and Hollweg, 1982). For this reason, the model particle distributions were taken to be isotropic and the waves were taken to be nondispersive, as well as parallel-propagating and left-polarized. The wave spectrum was taken to be a power law with constant spectral index γ. To simulate the interaction with ion-cyclotron waves, the spectrum was cut off at $\omega = \Omega_p$ in the proton reference frame.

The energization calculation proceeded as follows: The total plasma heating rate was obtained from the divergence of the flux of wave action of the saturated waves. This total was then distributed to the various ion species by taking the heating rate for each species proportional to the appropriate quasilinear resonant cyclotron heating term. The wave acceleration of each species was then the sum of the non-dissipative Alfven wave pressure and a term proportional to the dissipative heating. This procedure allowed energy to be supplied to the resonant particles on a convective time scale so that high resonant power levels were no longer required. These wave effects were incorporated into the spherically-symmetric, three-fluid, corotating solar wind equations which were integrated from 10 R_s out to 1 AU.

A typical result is shown in Figure 3. For this case, the proton and wave parameters were taken from the wave-driven high speed stream model of Hollweg (1978). The alpha particles, 4% by number, had their velocity and temperature set equal to the protons', and the spectral index was $\gamma = 2$. This result shows definite preferential acceleration and heating when the waves saturate at 19 R_s, but the differential speed falls far short of the observed Alfven speed value.

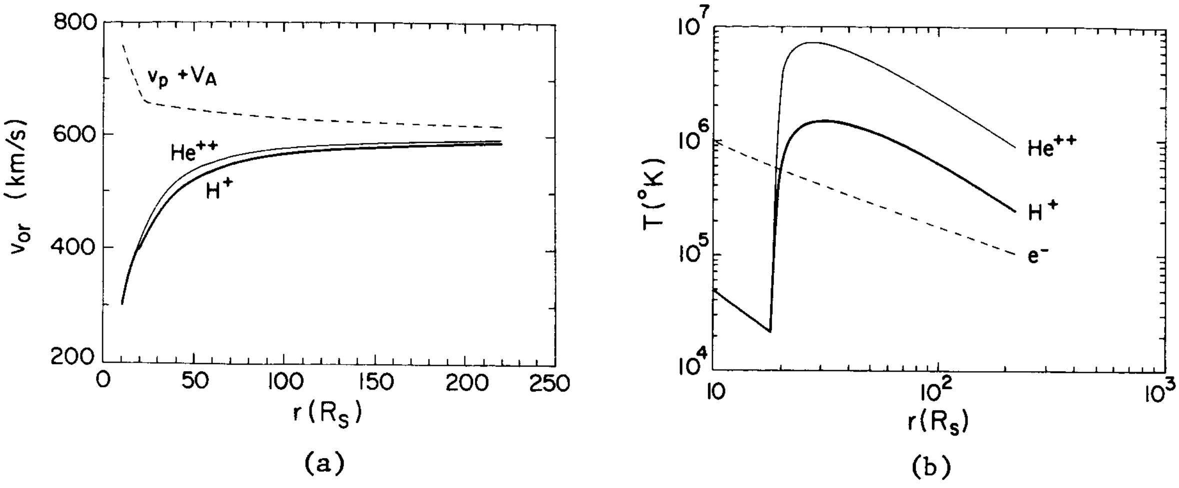
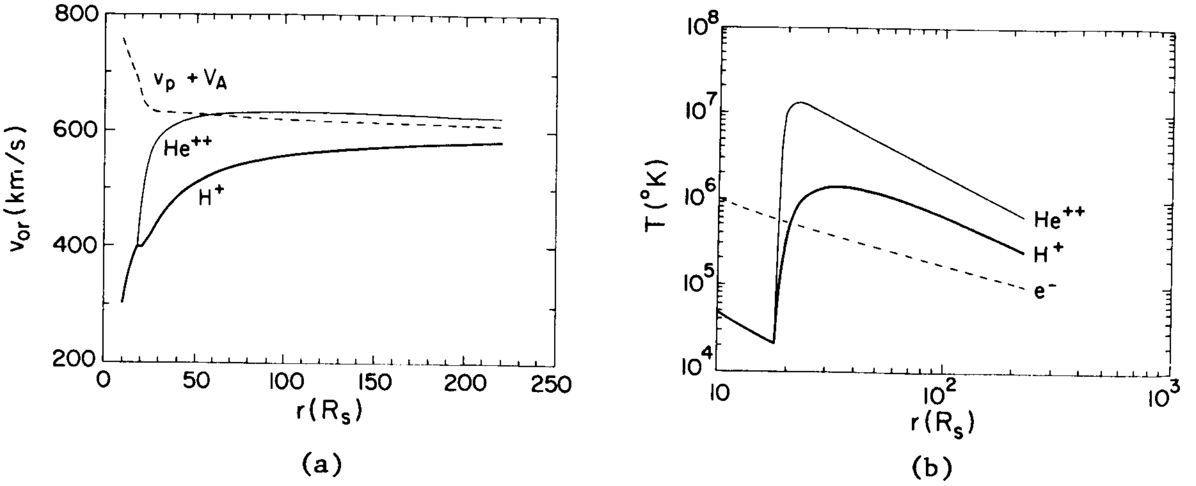


Figure 3. Ion radial speeds (a) and temperatures (b) from the model of Isenberg and Hollweg (1983) for $\gamma = 2$. Also shown in (a) is the radial component of the proton plus Alfven speed, and in (b) is the electron temperature.

Furthermore, the temperature ratio at 1 AU is only $T_\alpha/T_p = 3.6$, where we would hope to produce $T_\alpha/T_p \gtrsim 4$.

The preferential effects shown here proved essentially insensitive to changes in the initial particle velocities and temperatures. Increasing the initial wave intensity generated faster, hotter populations, but the values of $\Delta v_{\alpha p}$ and T_α/T_p changed very little. The only parameter left to vary was the spectral index and it is easy to see why γ is important. The quasilinear resonant interaction is proportional to the wave power at the resonant frequencies. When the protons and heavy ions are not moving with respect to one another, they resonate with waves near their respective gyrofrequencies. In the simplest picture, then, the power available to the ions is a factor of $(\Omega_i/\Omega_p)^\gamma$ larger than that for the protons where $\Omega_i = q_iB/(m_ic)$. Clearly, using a steeper wave spectrum will increase the preferential energization of the heavy ions.

The magnitude of the interaction is also proportional to the $(\text{charge/mass})^2$ of the particle, so one might expect the total resonant acceleration to be proportional to $(A_i/Z_i)^{\gamma-2}$. This simple picture would imply that a heavy ion could not be preferentially accelerated by this process unless $\gamma > 2$. In reality, this picture is complicated by the thermal speeds, which smear out the resonance; by the differential speed, which Doppler-shifts the resonances to different relative points; and by the fall-off in wave power at Ω_p. It turns out to be the power cutoff that is most important. If the cutoff is not included and the model wave spectrum is continued with the same slope to infinite frequency, the simple picture is verified by the numerical calculations: there is no preferential acceleration of heavy ions for $\gamma \leq 2$. The cutoff in the spectrum reduces the power in the proton resonant range and allows helium to be preferentially accelerated for $\gamma > 1.5$. To produce stronger preferential effects, γ must be increased to rarely observed values > 2, and it takes a $\gamma = 4.7$ to produce alpha particles with $\Delta v_{\alpha p} = V_A$ at 60 R_s as shown in Figure 4.



(a)

(b)

Figure 4. As in Figure 3 for $\gamma = 4.7$.

Once the alpha particles have been accelerated to $\Delta v_{\alpha p} \gtrsim V_A$ resonant interactions with right-polarized magnetosonic waves can become important. Beyond 80 R_s, in the case shown in Figure 4, almost 20% of the alpha population has sufficient parallel speed to resonate with the fast mode. However, this number is still small ($\sim$ 3% at 40 R_s) before the Alfven speed is reached and the right-hand interaction cannot play a significant role in the acceleration to V_A.

Heavier ions, with lower gyrofrequencies, are able to resonate with more intense waves and should be accelerated to higher speeds. However, this is only true if $\gamma > 2$ since the dissipative processes are proportional to $(A/Z)^{\gamma-2}$. When $\gamma = 2$, the determining factor is still the reduced proton resonant power due to the spectral cutoff, and the heavy ion velocities are the same as the alpha particle curves in Figure 3. When γ is increased it is found that oxygen ions, with A/Z near that of helium, are only slightly more accelerated. Acceleration of iron ions, on the other hand, is significantly enhanced over alpha particles, especially in the lower ionization states, such as Fe^{+8}, which reaches V_A at 50 R_s when $\gamma = 3$. Calculations by Marsch (1983) generate similar results for the interaction with left-polarized waves.

In summary, the Isenberg and Hollweg model of the resonant cyclotron interaction cannot explain the observed preferential acceleration and heating of heavy ions in the solar wind. To produce differential speeds on the order of those observed requires extremely steep wave spectra. Although there have been no direct observations of spectral slopes inside 60 R_s, all indications are that the spectra should be flatter there and spectral indicies of $\gamma = 4 - 5$ for $\omega < \Omega_p$ seem unlikely. The calculated temperature ratios, T_i/T_p, at 1 AU are also consistently lower than the mass-proportional values.

Several questions remain, for instance: What is the effect of allowing anisotropic particle distributions or including a spectrum of dispersive waves? These modifications should be investigated, but I suspect they will not provide substantially more preferential acceleration of heavy ions. The resonant interaction tends to energize particles in the perpendicular direction, so the requirement of isotropy amounts to an effective transfer of perpendicular energy into parallel energy and it does not seem that relaxing this assumption will produce greater acceleration. Furthermore, dispersive ion-cyclotron waves would interact with a smaller portion of the ion distribution than the assumed non-dispersive spectrum does, and would presumably be less effective in energizing the ions. It may also be important to consider the effect of including the solar wind alpha particles in the dispersion relation of the waves. Preliminary work (Isenberg, 1982) has shown that there may actually be no waves to accelerate heavy ions to speeds faster than the proton speed by the resonant interaction.

In conclusion, it appears that the resonant cyclotron interaction cannot be responsible for the observed preferential acceleration and heating, and we must look elsewhere to find a mechanism which produces the observed effects.

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