The Astrophysical Journal, 581:L125–L127, 2002 December 20

ION EFFECTIVE TEMPERATURES IN POLAR CORONAL HOLES: OBSERVATIONS VERSUS ION-CYCLOTRON RESONANCE

S. Patsourakos,[1,2] S. R. Habbal,[3,4] and Y. Q. Hu[5]
Received 2002 March 14; accepted 2002 November 6; published 2002 November 27

ABSTRACT

The resonant cyclotron interaction between ion-cyclotron waves and solar wind species is considered nowadays to be a strong candidate for heating and acceleration of protons, α-particles, and heavy ions. A crucial physical parameter for determining the amount and the location of significant heating and acceleration, which the different solar wind ions receive from the waves in the frame of the ion-cyclotron mechanism, is their charge-to-mass ratio q/m. Therefore, comparisons of ion temperatures derived from spectroscopic observations and calculated by ion-cyclotron models, for ions that span a broad range in q/m, would provide a rigorous test for such models. By using an ion-cyclotron model, we calculate the effective temperatures for 10 different ions that cover the range 0.16–0.37 in q/m. Effective temperatures correspond to unresolved thermal motions and wave motions. The good agreement between our calculations, based on the specific mechanism that we employed here (ion-cyclotron resonance) and on spectroscopic observations of effective temperatures in polar coronal holes, provides support that the above mechanism accounts for the energetics and kinematics of fast solar wind heavy ions. However, such an agreement does not prove that other potential mechanisms can be excluded.

Subject headings: solar wind — Sun: corona — Sun: UV radiation

1. INTRODUCTION

Major breakthroughs in our understanding of the fast solar wind resulted, and continue to emerge, from observations made by the *Solar and Heliospheric Observatory*. It seems that the fast solar wind primarily originates from the boundaries of the magnetic network in polar coronal holes (Hassler et al. 1999) and then continues its journey into the outer corona through the interplume regions (Giordano et al. 2000; Patsourakos & Vial 2000). Ultraviolet Coronagraph Spectrometer (UVCS) observations show that protons and minor ions are significantly hotter than electrons, with minor ions being preferentially heated and accelerated with respect to protons (e.g., Kohl et al. 1998; Li et al. 1998).

The latter results gave strong hints of the importance of the resonant interaction between ion-cyclotron waves and solar wind ions, for fast solar wind energetics and dynamics. The potential of the above mechanism for the preferential heating and acceleration of the solar wind ions was recognized earlier by a number of authors (e.g., Marsch, Goertz, & Richter 1982; Hollweg 1999; Hu & Habbal 1999; Hu, Habbal, & Li 1999; Cranmer, Field, & Kohl 1999). The essence of this mechanism is that high-frequency ion-cyclotron waves resulting either from a turbulent cascade of low-frequency Alfvén waves toward higher frequencies (e.g., Hu et al. 1999) or from microflaring in the network (e.g., Axford & McKenzie 1992; Moore et al. 1999) can dump their energy and momentum into plasma heating and acceleration when their frequency matches the local gyrofrequency of a given ion. Since the power spectrum of such waves is inversely proportional to the wave frequency, this means that ions with a smaller gyrofrequency will be more strongly heated and accelerated than ions with a larger gyrofrequency. Moreover, this preferential heating and acceleration of low-gyrofrequency ions takes place closer to the Sun than that of high-frequency ions, owing to the rapid decrease with distance of the magnetic field strength. When the dispersion of Alfvén waves by the minor ions is taken into account (e.g., Gomberoff, Gratton, & Gravi 1996; Hu 1999), the preferential heating and acceleration of minor ions are even more enhanced: minor ions act as "channels" for the wave heating to proceed from one gyrofrequency to the next.

One of the most useful spectroscopic observables in the solar corona is the ion effective temperature, namely, the FWHM of the observed spectral lines. It essentially corresponds to the combination of thermal and nonthermal (wave) motions along a given line of sight in the corona. Since effective temperatures are directly associated with ion temperatures, they provide a tool for testing heating mechanisms. For example, in the frame of the models mentioned in the previous paragraph, one can expect an ordering of the ion temperature with the ion gyrofrequency: the smaller the gyrofrequency, the larger the ion temperature. This has been demonstrated by Hu, Esser, & Habbal (2000), who compared UVCS observations of the effective temperatures of Mg x and O vi in the outer corona with model calculations. SUMER observations of a number of different ions in the inner corona (Tu et al. 1998) have also demonstrated the existence of such a trend. Let us note here that the relation between ion temperature and gyrofrequency, in the frame of the above mechanism, is not trivial; this results from the nonlinear character of the energy balance equation and the wave-particle interactions. What is clearly needed is to compare effective temperatures of a *large* number of ions spanning a broad range of gyrofrequencies derived from observations with detailed model predictions. This is the main objective of this work.

The present Letter is organized as follows. In § 2 we outline the numerical model used, while in § 3 we describe how effective temperatures were derived from the model and from observations for a number of different ions. Finally, in § 4 we describe our results and conclusions.

[1] US Naval Research Laboratory, 4555 Overlook Avenue, SW, Space Science Division, Code 7670P, Washington, DC 20375-5352; patsourakos@nrl.navy.mil.
[2] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK.
[3] University of Wales, Department of Physics, Penglais, Aberystwyth, Ceredigion SW23, 3BZ, UK.
[4] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[5] Department of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China.

2. NUMERICAL MODEL

The numerical model used here is described in full detail in Hu et al. (2000). The time-dependent conservation equations for mass, momentum, energy, and wave-action flux for a four-species plasma (protons, electrons, α-particles, and one minor ion) are self-consistently solved in a flow-tube geometry. All the relevant physical quantities are functions of the radial distance r only. The flow-tube cross-sectional area is given by $r^2 f(r)$, where $f(r)$ is a superradial expansion factor, which is given in Kopp & Holzer (1976). A Kolmogorov power spectrum describes the energy transfer from low-frequency left-hand–polarized Alfvén waves to high-frequency ion-cyclotron waves. The resonant interaction between the *ic* waves and the solar wind ions (protons, α-particles, and minor species) is responsible for their coronal heating and the acceleration. The distribution of wave energy to the ions is described by the quasi-linear theory of wave-particle interaction and by a cold-plasma dispersion relation. Minor ions can be approximately treated as test particles in the ambient proton α-particle wind as it has been demonstrated by Hu et al. (2000).

Grid points in space are distributed in such a way as to cope with the steep gradients in the inner corona. The corresponding numerical code is run for a sufficient time (≈35 days in physical time) until a steady state solution is reached; i.e., the mass, momentum, energy, and wave-action flux become time-independent. The calculations cover a distance range of 1 $R_\odot$–1.2 AU and a frequency range of 0–10^4 Hz. For more details, the interested reader may refer to Hu et al. (2000) and the references therein.

In Table 1, we give the initial conditions that we used for each numerical run. The ion densities are calculated by using the elemental abundances of Anders & Grevesse (1989) and the ionization equilibrium calculations of Shull & van Steenberg (1982). The Alfvén waves' power spectrum at the coronal base is the same as in Hu et al. (2000). The set of the initial conditions used corresponds to what may be termed as a "canonical" coronal hole (e.g., Withbroe 1988).

In the present work, we constructed a grid of solar wind solutions, employing the same initial conditions and comprising a number of different minor ions. The ions that we used are given in the following section. Their choice was dictated by existing spectroscopic observations of a large number of different ions at the same distance in polar coronal holes.

3. ION EFFECTIVE TEMPERATURES

3.1. *Model Calculations*

Effective temperatures $T_{\rm eff}^{\rm mod}$ (e.g., Esser et al. 1999) are defined as

$$T_{\rm eff}^{\rm mod} = T_i + \frac{m_i}{2k}\langle \delta v^2 \rangle, \tag{1}$$

where T_i and m_i are the ion temperature and mass, respectively, and $\langle \delta v^2 \rangle^{1/2}$ is the velocity amplitude associated with the Alfvén waves. By using equation (1) and the calculated T_i and $\langle \delta v^2 \rangle$, we derived the effective temperatures from the calculated grid of solutions. Uncertainties in the calculated $T_{\rm eff}^{\rm mod}$ were obtained by varying each one of the boundary conditions by $\pm 20\%$ about their value given in Table 1, calculating a new "perturbed" value for $T_{\rm eff}^{\rm mod}$ using equation (1), and finally determining the combined uncertainty.

TABLE 1

Boundary Conditions at 1 $R_\odot$[a]

Physical Parameter	Value
Electron density ($\mathrm{cm^{-3}}$)	2.5×10^8
Electron (=proton, α-particle, ion) temperature (K)	8.0×10^5
Magnetic field strength (G)	8
f_m	5
r_1 ($R_\odot$)	1.31
σ ($R_\odot$)	0.51
n_α/n_p	0.06
Wave amplitude (km $\mathrm{s^{-1}}$)	30

[a] Used for constructing the grid of our models described in the text: f_m, r_1, and σ refer to the formulation of the flow-tube cross section given in Kopp & Holzer 1976.

3.2. *Observations*

Effective temperatures $T_{\rm eff}^{\rm obs}$ were determined from the observations of Hassler et al. (1990), Tu et al. (1998), and Banerjee et al. (2000) by attributing the line width of their observed spectral lines to an effective temperature according to the following equation:

$$T_{\rm eff}^{\rm obs} = \frac{m_i}{2k}\Delta\lambda^2\left(\frac{c}{\lambda}\right)^2, \tag{2}$$

where $\Delta\lambda$ is the $1/e$ width of the line profiles, which were represented by a Gaussian function. As far as uncertainties in $T_{\rm eff}^{\rm obs}$ are concerned, we used those given in the corresponding references leading to an upper limit of 30%. However, the uncertainties in $T_{\rm eff}^{\rm obs}$ may be even larger given the fact that the uncertainties employed here correspond to the effect of counting statistics only.

4. RESULTS AND DISCUSSION

In the inner corona, densities are still fairly high, and thus minor ions can lose energy as a result of Coulomb collisions with protons while gaining energy from the ion-cyclotron interactions. Both of these processes depend on q/m and will thus tend to order the minor ion temperatures according to q/m. However, we believe that the ion-cyclotron interactions dominate the Coulomb collisions in setting the minor ion temperatures.

The comparison between the calculated $T_{\rm eff}^{\rm mod}$ and the observed $T_{\rm eff}^{\rm obs}$ are given in Table 2 and plotted in Figure 1. We also applied a least-squares fit to the observational data using a linear function and taking into account their uncertainties. A trend of increasing $T_{\rm eff}^{\rm obs}$ with decreasing q/m can be seen. $T_{\rm eff}^{\rm mod}$ increases with decreasing q/m following the expectations of the ion-cyclotron resonance mechanism. This increase is more rapid at 1.18 $R_\odot$ than at 1.05 $R_\odot$ since most of the superradial expansion of the flow tube, and thus of the rapid decrease in gyrofrequency, starts well above the latter distance. The $T_{\rm eff}^{\rm obs}$ values are less "well-ordered" with q/m than the $T_{\rm eff}^{\rm mod}$ values are, but they still demonstrate a weaker trend. We note also that at both distances, $T_{\rm eff}^{\rm obs} > T_{\rm eff}^{\rm mod}$ for most of the ions considered, although this trend is reversed for the lower gyrofrequency (and for more strongly heated and accelerated ions). The uncertainties in $T_{\rm eff}^{\rm mod}$ have a tendency to increase with decreasing q/m; this may be due to the fact that at small q/m, the effects of resonance between the waves and the ions are much more enhanced. What we can conclude from Figure 1 is that the calculated and observed $T_{\rm eff}$ values are in good agreement, to within a factor of at most 2 within their corre-

TABLE 2

Observed and Calculated Effective Temperatures[a]

Ion	q/m	$\log T_{\rm eff}^{\rm obs}$	Reference	$\log T_{\rm eff}^{\rm mod}$
At a Distance of 1.05 $R_\odot$				
Mg X	0.37	6.55	α	$6.31^{+0.01}_{-0.11}$
O VI	0.31	6.45	γ	$6.23^{+0.02}_{-0.04}$
Ne VIII	0.29	6.55	β	$6.27^{+0.01}_{-0.04}$
Ne VII	0.28	6.5	β	$6.28^{+0.02}_{-0.02}$
Mg VIII	0.28	6.55	β	$6.33^{+0.31}_{-0.1}$
Si VIII	0.24	6.4	β	$6.41^{+0.04}_{-0.02}$
Si VII	0.21	6.55	β	$6.51^{+0.02}_{-0.04}$
Fe XI	0.17	6.65	β	$6.81^{+0.28}_{-0.06}$
Fe X	0.16	6.75	β	$6.92^{+0.1}_{-0.06}$
At a Distance of 1.18 $R_\odot$				
Mg X	0.37	6.64	α	$6.54^{+0.04}_{-0.06}$
O VI	0.31	6.61	γ	$6.55^{+0.11}_{-0.06}$
Ne VIII	0.29	6.7	β	$6.51^{+0.29}_{-0.4}$
Ne VII	0.28	6.7	β	$6.65^{+0.13}_{-0.08}$
Mg VIII	0.28	6.6	β	$6.72^{+0.42}_{-0.1}$
Si VIII	0.24	6.8	β	$7.02^{+0.29}_{-0.13}$
Fe XII	0.19	6.8	β	$7.64^{+0.53}_{-0.49}$

[a] The first column gives the ion used, the second column gives its charge-to-mass ratio, the third column gives the logarithm (base 10) of the observed effective temperatures ($T_{\rm eff}^{\rm obs}$), the fourth column gives the references from which the $T_{\rm eff}^{\rm obs}$ values were extracted: α = Hassler et al. 1990, β = Tu et al. 1998, γ = Banerjee et al. 2000, and the fifth column gives the logarithm (base 10) calculated from the model effective temperatures ($T_{\rm eff}^{\rm mod}$) and the uncertainties in $T_{\rm eff}^{\rm mod}$.

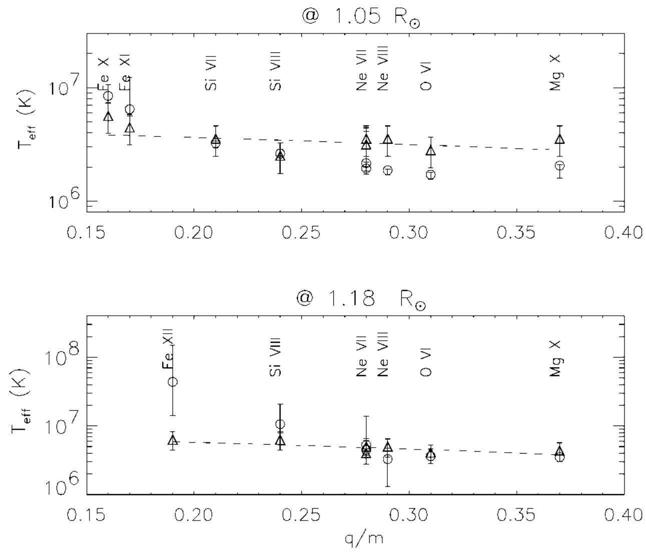

Fig. 1.—Effective temperatures (*circles*: model; *triangles*: observations) for a number of different ions as a function of their q/m ratio at 1.05 $R_\odot$ (*top panel*) and 1.18 $R_\odot$ (*bottom panel*). A least-squares fit to the observed effective temperatures is also shown as a dashed line.

sponding uncertainties, for all but one of the cases. The point of maximum disagreement between the observations and the calculations (a factor of ≈6) corresponds to observations made in the Fe XII line at 1.18 $R_\odot$. This line is particularly faint in coronal hole regions, and observations may have underestimated its true width: the poor photon statistics in the line wings could be a hampering factor for resolving the full line and thus the corresponding $T_{\rm eff}$. Furthermore, if electrons are relatively cool in coronal holes, emission in the Fe XII line should primarily originate from hotter (noncoronal hole) regions.

It is interesting to note how well the calculations agree with the observations, despite a number of simplifying assumptions included in the calculations, the inclusion of one minor ion at any time, neglecting the effect that the other ions may have on the wave dispersion, and the use of a cold plasma relation that overestimates the effects of the waves. Moreover, the noninclusion of anisotropic temperature distributions into our model should not interfere with our results since coronal ions start to develop highly anisotropic temperature distributions from a distance of about 1.5 $R_\odot$ (Li et al. 1998, 1999), which is well above the maximum distance considered here. Regardless of its simplifications, the four-fluid model that we used seems capable of capturing the essential elements of fast solar wind energetics and dynamics, as it was also shown for the outer corona and 1 AU in Hu et al. (2000).

The overall good agreement between the observed and calculated $T_{\rm eff}$ values, for 10 different ions corresponding to q/m ratios that span a broad range from 0.16 to 0.37, provides a new supporting argument in favor of the ion-cyclotron mechanism for the heating and acceleration of fast solar wind ions in polar coronal holes. However, this good agreement does not imply that other potential mechanisms can be excluded.

Research was supported in part by NASA, ONR, and PPARC. We thank the referee V. Hansteen for helpful comments/suggestions.

REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Axford, W. I., & McKenzie, J. F. 1992, in Proc. Third COSPAR Colloq., Solar Wind Seven, ed. E. Marsch & R. Schwenn (New York: Pergamon), 1
Banerjee, D., Teriaca, L., Doyle, J. G. & Lemaire, P. 2000, Sol. Phys., 194, 43
Cranmer, S. R., Field, G. B., & Kohl, J. L. 1999, ApJ, 518, 937
Esser, R., Fineschi, S., Dobrzycka, D., Habbal, S. R., Edgar, R. J., Raymond, J. C., Kohl, J. L., & Guhathakurta, M. 1999, ApJ, 510, L63
Giordano, S., Antonucci, E., Noci, G., Romoli, M., & Kohl, J. L. 2000, ApJ, 531, L79
Gomberoff, L. F., Gratton, F. T., & Gravi, G. 1996, J. Geophys. Res., 101, 15,661
Hassler, D. M., Dammasch, I. E., Lemaire, P., Brekke, P., Curdt, W., Mason, H. E., Vial, J.-C., & Wilhelm, K. 1999, Science, 283, 810
Hassler, D. M., Rottman, G., Shoub, E. C., & Holzer, T. E. 1990, ApJ, 348, L77
Hollweg, J. V. 1999, J. Geophys. Res., 104, 505
Hu, Y. Q. 1999, in AIP Conf. Proc. 471, Solar Wind Nine, ed. S. R. Habbal, R. Esser, J. V. Hollweg, & P. A. Isenberg (Woodbury: AIP), 285
Hu, Y. Q., Esser, R., & Habbal, S. R. 2000, J. Geophys. Res., 105, 5093
Hu, Y. Q., & Habbal, S. R. 1999, J. Geophys. Res., 104, 17,045
Hu, Y. Q., Habbal, S. R., & Xing, L. 1999, J. Geophys. Res., 104, 24,819
Kohl, J. L., et al. 1998, ApJ, 501, L127
Kopp, R. A., & Holzer, T. E. 1976, Sol. Phys., 49, 43
Li, X. L., Habbal, S. R., Hollweg, J. V., & Esser, R. 1999, J. Geophys. Res., 104, 2521
Li, X. L., Habbal, S. R., Kohl, J., & Noci, G. 1998, ApJ, 501, L133
Marsch, E., Goertz, C. K., & Richter, A. K. 1982, J. Geophys. Res., 87, 5030
Moore, R. L., Falconer, D. A., Porter, J. G., & Suess, S. T. 1999, ApJ, 526, 505
Patsourakos, S., & Vial, J.-C. 2000, A&A, 359, L1
Shull, J. M., & van Steenberg, M. 1982, ApJS, 48, 95
Tu, C.-Y., Marsch, E., Wilhelm, K., & Curdt, W. 1998, ApJ, 503, 475
Withbroe, G. L. 1988, ApJ, 325, 442