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Erratum: "Perpendicular Ion Heating by Cyclotron Resonant Dissipation of Turbulently Generated Kinetic Alfvén Waves in the Solar Wind" (2019, ApJ, 887, 63)

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Our recent published article contains an error and several typos.

The published article proposed that a turbulent spectrum of highly oblique kinetic Alfvén waves (KAWs) can heat solar wind ions in the directions perpendicular to the large-scale magnetic field through their cyclotron resonant dissipation. We presented a simplified computational example of heating in a $\beta = 0.1$ plasma, where β is the ratio of the thermal ion pressure to the magnetic pressure. The description of the wave–particle interactions and the computations of ion heating are all correct as presented there, and this cyclotron resonant damping remains a physically valid mechanism for perpendicular ion heating in a turbulent plasma.

However, in Section 4.1 we attempted to estimate the physical time corresponding to the duration of the computation in the applicable region (heliocentric radial position ~20 solar radii). This estimate was incorrect and our stated value was unrealistically short. The correct value of the computational time step is $\tau = \Omega_p\ t = [2\ \pi\ (\langle \delta B^2 \rangle / B_o^2)]^{-1} \sim 5 \times 10^{-2}\ (\langle \delta B^2 \rangle / B_o{}^2)^{-1}$, where $(\langle \delta B^2 \rangle / B_o{}^2)$ is the turbulent intensity evaluated at $k_\perp \lambda = 1$ and λ is the proton inertial length. Thus, the 4×10^5 time steps in the published article, with $\Omega_p = 20\ \mathrm{s}^{-1}$, corresponds to $10^3\ (\langle \delta B^2 \rangle / B_o{}^2)^{-1}$ s. Typical estimates of the turbulent intensity at small scales in the inner heliosphere solar wind give $(\langle \delta B^2 \rangle / B_o{}^2) \sim 10^{-4}$–$10^{-6}$, so the proton evolution in that computation cannot describe the heating of a parcel of solar wind plasma at a specific location.

A more appropriate means of evaluating this KAW turbulent dissipation process is to compare the quasilinear proton heating rate from the computation to an estimated turbulent cascade rate implied by the assumed fluctuation spectrum. During the computation, the proton perpendicular temperature increased by a factor of 6.7, so the heating rate, $\Delta T_\perp / \Delta t = 6.7 (2 \times 10^4)^{-1} T_o \Omega_p (\langle \delta B^2 \rangle / B_o{}^2)$. The computation started with a plasma $\beta = 0.1$, so $T_o = 0.1 V_A{}^2$, giving a heating rate of $\Delta T_\perp / \Delta t = 3.35 \times 10^{-5} (\langle \delta B^2 \rangle / B_o{}^2) \Omega_p V_A{}^2$.

The Kolmogorov turbulent cascade rate is proportional to $k\,Z^3$, where $Z\,(k)$ is the fluctuation amplitude in Alfvén units. Since this rate is supposed to be constant in the inertial range of a turbulent spectrum, we evaluate it here at the proton inertial scale giving $\varepsilon_K = CZ^3 / \lambda = C\,[(1 + R_\mathrm{A})(\langle \delta B^2 \rangle / B_o{}^2) V_A{}^2]^{3/2} \Omega_p / V_A$, where the Alfvén ratio, R_A, is the ratio of the kinetic to magnetic energy of the turbulent fluctuations, and C is a proportionality constant.

For a quantitative estimate of this cascade rate, we refer to the observational comparison of turbulent heating rates and cascade rates in the solar wind at 1 au by Vasquez et al. (2007). That work tested the theoretical prediction for the inertial range cascade rate equivalent to $\varepsilon_K^{\mathrm{th}} = [(1 + R_\mathrm{A})(\langle \delta B^2 \rangle / B_o{}^2) V_A{}^2 / C_K]^{3/2} / \lambda$ in our notation, where C_K is a theoretically determined constant taken to be $C_K = 1.6$. Vasquez et al. found that this predicted cascade rate was far too high at 1 au to correspond to the observed proton heating. Setting $R_\mathrm{A} = 1/2$, they concluded that the theoretical expression should be multiplied by an additional factor ~1/20.

It is not known to what extent this observational result at 1 au is related to the conditions at 20 solar radii. We will simply take the Vasquez et al. estimate at face value, with the understanding that its implications may only be valid within an order of magnitude. This yields a cascade rate $\varepsilon_K \sim 0.05[(1.5/1.6)(\langle \delta B^2 \rangle / B_o{}^2) V_A{}^2]^{3/2} \Omega_p / V_A = 4.5 \times 10^{-2} (\langle \delta B^2 \rangle / B_o{}^2)^{3/2} \Omega_p V_A{}^2$.

Comparing these estimates implies that the quasilinear heating rate could be comparable to the expected cascade rate if $(\langle \delta B^2 \rangle / B_o{}^2)^{1/2} \sim 7.4 \times 10^{-4}$, or $(\langle \delta B^2 \rangle / B_o{}^2) \sim 5.4 \times 10^{-7}$. This value for the turbulent fluctuation intensity at the proton inertial length is only a factor of 2 smaller than the estimated lower bound of the intensity at 20 solar radii. Given the very broad range of quantitative estimate in this comparison, the implications of the simplified computation in the published article are not unrealistic when applied to the $\beta = 0.1$ regions of the solar wind.

Thus, the mechanism of resonant cyclotron damping of turbulent KAWs remains a physically viable explanation for ion perpendicular heating in the solar wind. We will continue to investigate the effects of increasingly realistic models of this process in future work.

The typographical errors appeared in Equations (2), (7), and (14). Here, we present the corrected equations:

$$\delta \boldsymbol{E} = \left[\frac{\omega}{2k_\parallel} (\lambda_e{}^2 k_\perp{}^2 + \Gamma_2 + 1)\hat{\boldsymbol{x}} + i\frac{\Omega}{k_\parallel}\Gamma_1 \hat{\boldsymbol{y}} + \frac{\omega}{2k_\perp}(\lambda_e{}^2 k_\perp{}^2 + \Gamma_2 - 1)\hat{\boldsymbol{z}} \right] \delta B_y, \tag{2}$$

$$G \equiv \left(1 - \frac{k_\parallel\, v_\parallel}{\omega}\right) \frac{\partial}{\partial v_\perp} + \frac{k_\parallel v_\perp}{\omega} \frac{\partial}{\partial v_\parallel}, \tag{7}$$

$$M_{||,||} = \left(\frac{v_\perp}{V_{\rm ph}}\right)^2; \quad M_{||,\perp} = \frac{v_\perp (V_{\rm ph} - v_{||})}{{V_{\rm ph}}^2};$$
$$M_{\perp,\perp} = \left(\frac{V_{\rm ph} - v_{||}}{V_{\rm ph}}\right)^2. \tag{14}$$

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Reference

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