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ANGLE SCATTERING AND FORMING THE HYDROGEN DOPPLER PROFILE IN PROTON AURORA

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Abstract. The main patterns of the proton precipitation in the atmosphere were described already in the 1970s. The blue-shifted Doppler profiles of hydrogen lines are associated with proton precipitations. It is accepted that these profiles contain information about distribution in the precipitated particle flux. However, some peculiarities of these profiles, namely, the red-shifted wing are not well understood. This red wing is usually explained by large angle scattering at the collision energies less than 1 keV. However, this assumption contradicts with available information about cross sections.

Here we analyze the forming of the hydrogen Doppler profile by detailing individual scattering reactions and electronic states. Theoretical estimations are tested by a new version of a transport code modeling penetration of the proton-hydrogen atom flux in the Earth's atmosphere. The Monte-Carlo method with a collision-by-collision algorithm has been used. The results have been compared with available observations.

1. Introduction

The blue-shifted Doppler profiles of hydrogen lines are associated with proton precipitations [Vegard, 1939]. It is accepted that these profiles contain information about distribution in the precipitated particle flux. An example of the Doppler-shifted zenith profile of Balmer-α line observed in evening sector of the auroral oval [Borovkov et al., 2005] is shown in Fig.1. An estimation of the blues-shifted wing of the profile gives the average energy of precipitated protons 33 keV. However, some typical peculiarities of these profiles, namely, the red-shifted wing are not well understood. One can see in Fig.1 that significant part of the emission is shifted in red side (to longer wavelengths). The large red wing is also observed in the region of cusp where the typical energy of proton precipitation is a few keV.

The red-shifted emission means that the excited hydrogen atom moved upward when it emitted the photons. The formation of a large flux of upward hydrogen atom flux is not fully understood. There are two obvious mechanisms which could form the upward flux: collisional angle scattering and magnetic mirroring of protons in the dipolar magnetic field.

On average, the angle scattering of protons and hydrogen atoms of auroral energies is very small. If we compare the average scattering angles of protons and electrons of the same velocity, when it is possible to obtain an estimation:

$$\theta_p/\theta_e \approx m_p/m_e = 1836 \qquad (1)$$

There are two useful characteristics of a particle's transport in a matter: the transport length l_{tr} characterizes the typical length of the particle track when it loses information about its initial direction of motion; and the penetration depth l_{pen} which characterizes the length of the particle track in the matter. The penetration depth is inversely proportional to the total cross section of collisional scattering, $l_{pen} \sim \sigma_{tot}^{-1}$. For scattering of protons and electrons in atmospheric gases the total cross sections are the same order. However the transport length is:

$$l_{tr} \approx n_o^{-1}\,\sigma_{tot}^{-1}\,\theta_a^{-2} \qquad (2)$$

Therefore, from (1) and (2) it is clear that the transport length for protons is 6 decimal orders larger than for electrons. Roughly speaking, the proton flux has to lose its energy faster when its initial direction. The electron flux has the opposite tendency.

Direct transport simulation for the proton-hydrogen atom flux in the atmosphere by the Monte-Carlo method supports these speculations: averaged collisional angle scattering cannot explain the upward motion of hydrogen atoms [Kozelov and Ivanov, 1992]. The magnetic mirroring effect leads to a small upward flux of H-atoms also [Kozelov, 1993], but the protons mirrored at high altitudes have a minor chance for electron capture and, therefore, cannot play a significant role in hydrogen emission.

Here we are testing the possible explanation of the large upward flux of hydrogen atoms which produced the hydrogen emission. The explanation is based on specification of the angle scattering for reactions of electron capture with excitation of different states of hydrogen atoms.

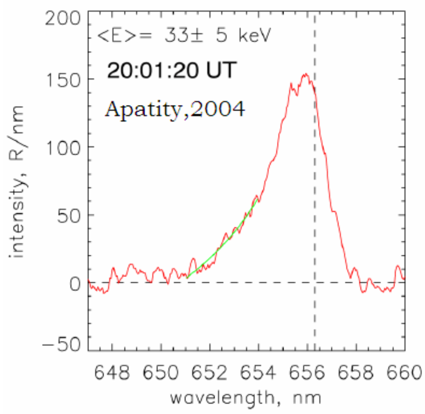

Fig. 1. Doppler-shifted profiles of hydrogen line Hα [Borovkov et al., 2005] observed in the evening sector of the auroral oval.

2. Angle scattering model and cross section data

The above mentioned problem with explanation of the hydrogen line profile may be resolved if the larger angle scattering (redistribution) is assumed. This way is using the model of [Galand et al., 1997]. According to detailed description of the model parameters in [Lanchester et al., 2003], the phase function used in the algorithm (Eq.7 in [Galand et al., 1997]) is arbitrarily set to a large constant value for collisional energies <1 keV. This assumption leads to large angle scattering of the low energetic particles, therefore fast angular redistribution occurs. However, this assumption contradicts with known information about the cross sections. Fig.2 presents a comparison of the energy dependence of the average scattering angle deduced from cross sections for p - N_2, p-H collisions, and deduced from the [Galand et al., 1997] redistribution function. One can see the disagreement well. For E = 1 keV the Galand's assumption gives the scattering angle which is on factor 10 higher. A large upward proton flux should be typically observed if this large angle scattering is true. Satellite observations at low altitudes (FAST satellite, for example) don't give support of this assumption (Sometimes there are strong upward beams of protons (conics), but these events are attributed as a result of wave-particle interactions [Rauch et al., 1993]).

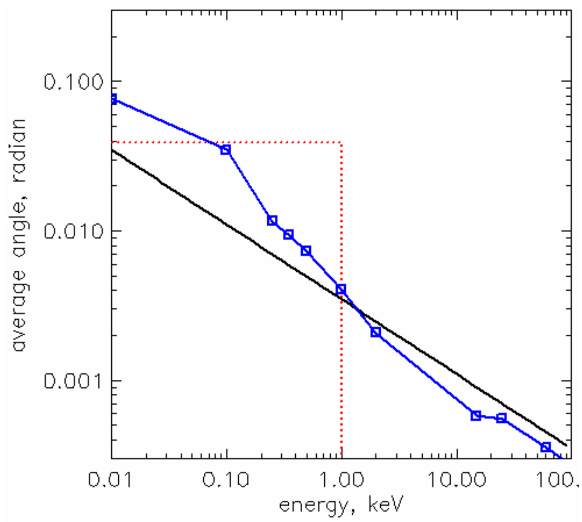

Fig. 2. Average scattering angle as a function of collisional energy: black line – for p-N_2 collisions [Kozelov and Ivanov, 1992]; blue squares and line – for p-H collisions, deduced from [Krstić and Schultz, 1998; Killian et al., 2004; Shakeshaft, 1978]; dashed line – deduced from [Galand et al., 1997] model.

We should stress that to explain the red Doppler shift only the upward flux of *excited* hydrogen atoms is needed. Have we any reasons to assume a specification of the angle scattering for reactions of electron capture with excitation of different states of hydrogen atoms? Fig.3 presents an example of the differential cross sections for charge transfer reactions of protons and hydrogen atoms. The reaction with excitation of the resulting hydrogen atom to the 2s state was considered separately. One can see that nearly forward scattering peaks are less pronounced for the capture reaction with excitation. Therefore we can say that on average the scattering angle for such reactions should be large. The resonant charge transfer reactions for p-H and p-O reactions at small energies (<1 keV) are very similar, and these are the most probable reactions for precipitated protons at high altitudes of the Earth's atmosphere. We can check our assumptions by direct numerical simulations.

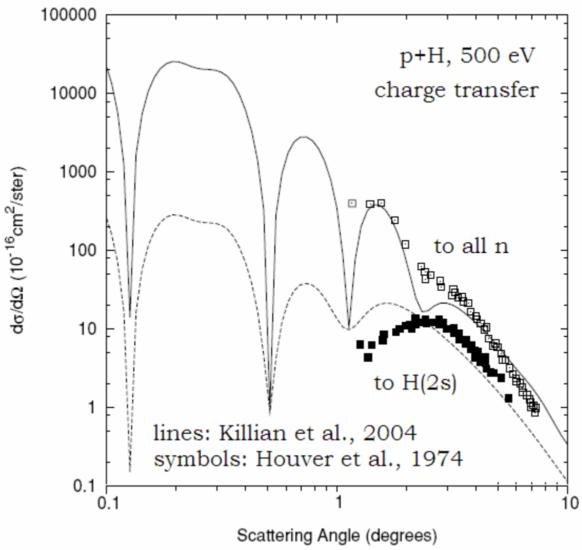

Fig. 3. Differential cross sections of the charge transfer for protons in the atomic hydrogen, reproduced from [Killian et al., 2004]. Lines - theoretical calculations by [Killian et al., 2004], symbols – measurements by [Houver et al., 1974].

3. Transport model and simulations

Here we use a transport Monte-Carlo model based on 'collision-by-collision' algorithm described in [Kozelov and Ivanov, 1992; Kozelov, 1993]. The atmosphere is simulated by the MSIS model, with three gases are taken into account: N_2, O_2, O. The model contains detailed partial cross sections: 19 - for p-N_2 collisions, 22 - for p-O_2, 9 - for p-O, 25 - for H-N_2, 17 - for H-O_2, and 12 - for H-O collisions. Effects of the dipole magnetic field can be turned on or off separately for protons and neutral atoms, see [Kozelov, 1993].

For simplicity, here we will not randomize the scattering angle for each collision, but an average scattering angle for given collisional energy will be taken into account. 4 different models for the scattering angle approximation have been tested: 1) forward scattering for all collisions, 2) average angle scattering from [Kozelov and Ivanov, 1991] for all collisions, 3) average angle scattering deduced from Galand' model, 4) average angle scattering from [Kozelov and Ivanov, 1992] for all collisions with exceptions of electron capture reactions for E<1 keV with excitation of higher than ground states of the hydrogen atom:

$$p+H \rightarrow H^*(>1s)+p \qquad (3)$$

For these exceptions we will use isotropic angle scattering.

The altitude profiles of energy deposition rate have been simulated for these 4 types of angle scattering and 2 cases of the dipolar magnetic field accounting ("turn off" and "turn on", see [Kozelov, 1994]). The proton precipitations with small initial energy are the most interesting for the forming of the upward hydrogen atom flux and red wing of the Doppler profile. The results of model simulation for monoenergetic (E_0=1 keV) proton precipitation with isotropic in the downward hemisphere angle distribution are presented in Fig.4.

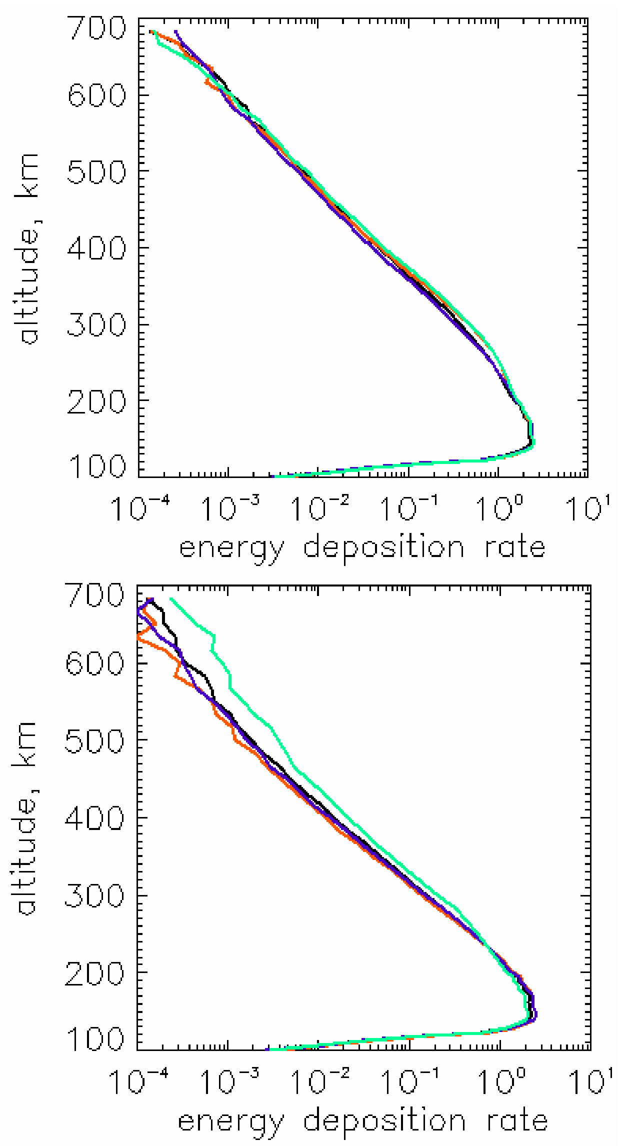

Fig. 4. Altitude profiles of energy deposition rate for monoenergetic proton flux, isotropic in the downward hemisphere. Angle scattering model used: green - forward; red – average angle [Kozelov and Ivanov, 1992]; blue - average angle deduced from [Galand et al., 1997]; black - isotropic for capture with hydrogen emission. Top panel: magnetic field is turn off; bottom panel: dipolar magnetic field is turn on.

One can see that there is no difference between the altitude profiles calculated by models with non-zero (not forward) angle scattering. This is true for models with dipolar magnetic field as well as for models without the field. The largest differences with from the forward scattering model are observed at altitudes >400 km in the case of "turned on" magnetic field.

The formalism of the calculation of the Doppler profiles from transport algorithms is well-known; see, for example, [Lorentzen et al., 1998]. The zenith profiles of the Balmer-α hydrogen line simulated by the considered models are shown in Fig.5.

The profiles are significantly different. Among the models without dipolar magnetic field, the less difference observed for the scattering of types 1 (forward scattering) and 2 (scattering on average angle from [Kozelov and Ivanov, 1991] for all reactions). The average scattering on Galand's average angle gives a larger red wing, but the scattering of type 4, with separations of final excited states, gives even longer red wing.

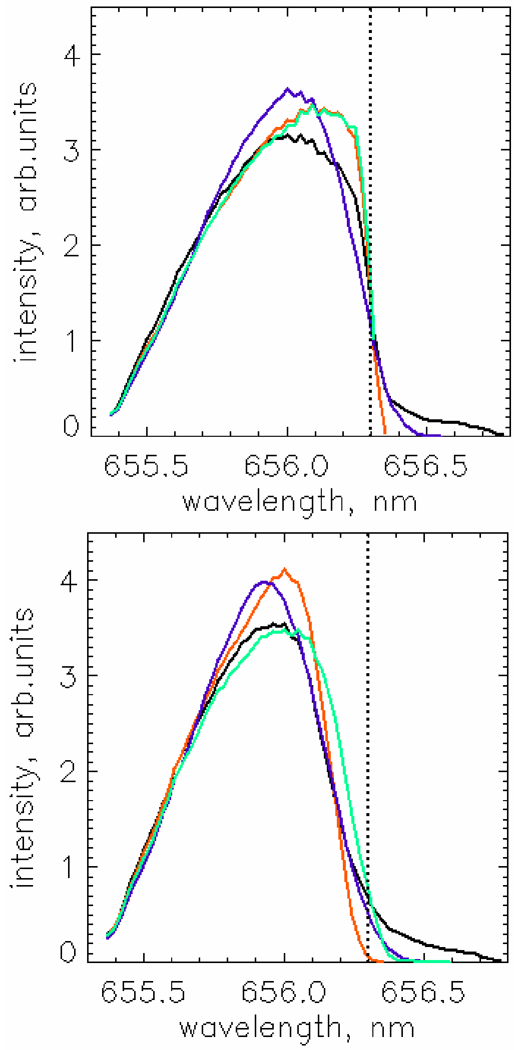

Fig. 5. Simulated zenith profiles of the Balmer-α hydrogen line. The models and color lines are the same as for Fig.4.

Influence of the dipolar magnetic field changes the hydrogen line profiles in all models. However, the scattering model with separations of final excited states gives the longest red wing. From these simulation results we can deduce that the assumption about isotropic scattering for collisional reactions like Eq.3

gives a long red wing in simulated profiles. Obviously that the assumption gives overestimated values of the scattering angle for these reactions. However, for this model the average scattering angle (over all reactions including capture to ground state) agrees well with cross section data. In reality the scattering angles for capture with excitation should be less than for isotropic scattering. By our simulation we have demonstrated that it is not necessary to assume the large scattering for all charge exchange reactions, like done in [Galand et al., 1997] model.

4. Conclusions

Here we analyze the forming of the hydrogen Doppler profile by detailing individual scattering reactions and electronic states. This consideration gives us a possibility to explain an existence of the red wing in the hydrogen line profiles and small average angle scattering for particles in proton precipitations according to available cross section data. We note that formation of the red wing in the Doppler profile cannot be explained only by collisional scattering and magnetic mirroring. Larger angle scattering in collisional reactions with final excited states of hydrogen should be taken into account.

This explanation will be extensively tested in future model simulations.

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