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Introduction to special section: Proton precipitation into the atmosphere

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1. Introduction

Energetic protons, precipitating into the atmosphere, interact with the ambient neutrals, leading to excitation, ionization, elastic scattering, and, for MeV protons, dissociation. In addition, a proton can capture an electron, producing an energetic H atom, which has enough energy to interact, in turn, with the ambient neutrals. This H atom can also get stripped of its electron, becoming a proton again. Because of these charge-changing reactions, the incident proton beam penetrating the atmosphere becomes a mixture of protons and H atoms [see, e.g., *Rees*, 1989]. In addition, electrons are produced inside the proton beam through ionization and stripping reactions. These electrons, also called proto-electrons, can be energetic enough to excite and ionize atmospheric gases. All these interactions lead to electron and ion production, heating, and excitation, and to the spectacular auroral emissions. Excitation can be produced directly by the energetic particles or indirectly via chemistry. Protons in the keV energy range deposit most of their energy in the E region (100-160 km), whereas MeV proton energy deposition will occur at lower altitudes, typically in the D region and below.

H emissions resulting from excited H atoms inside the proton beam are a unique signature of proton precipitation. In the region where precipitating particles deposit their energy, the ambient H atom density is too low to produce a significant amount of auroral emissions from excitation by energetic particle precipitation. Since the hydrogen atoms retain the energy of the protons on charge exchange, the emissions of excited H atoms are Doppler-broadened and -shifted. Observed from ground along the magnetic zenith, the H emission profile is blue-shifted, because most of the energetic H atoms are moving downward. Unlike electron aurora, proton aurora is diffuse owing to the contribution of H atoms whose path, independent of the magnetic field configuration, produces a spreading of the incident proton beam [see, e.g., *Eather*, 1967].

Proton precipitation is observed at different locations around the Earth. At high latitudes, keV protons contribute to the auroral ovals, precipitating from the plasma sheet, the magnetosheath, the low-latitude boundary layer, and through the cusp [see, e.g., *Hardy et al.*, 1989]. MeV protons from solar particle events [*Gosling*, 1993] induce the polar cap absorption (PCA) events. The additional E and D region (20-120 km) ionization caused by proton precipitation results in the enhancement of absorption of the background high-frequency cosmic radio waves across the entire polar cap [see, e.g., *Bailey*, 1964]. Finally, energetic neutral atoms (ENA) and protons originating in the ring current produce low-latitude and midlatitude aurorae [see, e.g., *Rassoul et al.*, 1993].

Since publication of the review papers on proton precipitation by *Eather* [1967] and *McNeal and Birely* [1973], tremendous progress has been made in modeling as well as on instrumental performance, and the interest in proton precipitation has been getting stronger. To illustrate this, two proton workshops were organized during the coupling energetics and dynamics of atmospheric regions (CEDAR) meetings in 1994 by R. Smith and in 1999 by M. Galand. Numerous instruments, both ground-based and satellite-borne, have recently been deployed to observe proton aurora, as illustrated in Figure 1. The effort invested in auroral proton studies has lead to the development of more comprehensive models describing the interaction of energetic protons with the atmosphere. These tools have been relevant for the analysis of space-/ground-based observations. Such studies have shown that protons can have a significant influence on the ionosphere and the thermosphere through ionization, conductivity changes, heating, and composition changes [e.g., *Shumilov et al.*, 1992; *Galand et al.*, this issue]. These are all quantities of great concern in space weather. In addition, the large-scale morphology of proton aurora is a better indicator than electrons for mapping observed auroral features to magnetospheric regions or processes.

Consequently, it is time to emphasize to the ionospheric and magnetospheric communities the role of energetic protons in the atmosphere. In addition, a review of proton studies is all the more timely, since very recent and future missions (e.g., Imager for Magnetopause-to-Aurora Global Exploration (IMAGE), Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED), National Polar-orbiting Operational Environmental Satellite System (NPOESS)) are expected to acquire relevant data on proton aurora in the years ahead. The purpose of this special section of the *Journal of Geophysical Research* is to provide a forum for an overview of the current state of the field and to open a discussion of remaining questions that address the need

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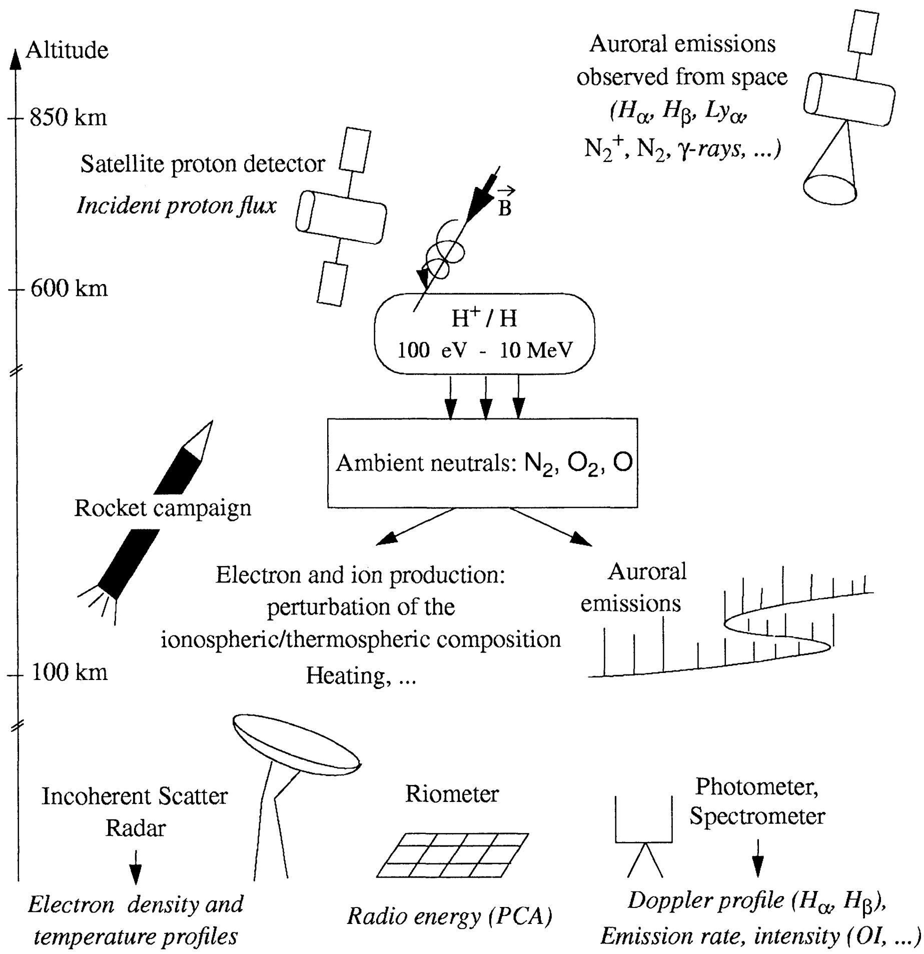

Figure 1. Overview of the observations related to proton precipitation. PCA, polar cap absorption.

for future studies. Based on the CEDAR 99 proton workshop, the different subjects discussed here are the following: the origin and characteristics of the incident protons, H emission observations and analysis, the modeling of proton transport in the atmosphere, and the coordinated observations of proton aurora. While emphasizing recent progress in proton issues, sections 2-6 do not give a comprehensive review of proton studies but serve to introduce the papers of this special section.

2. Incident Energetic H^+ and H Fluxes Precipitating Into the Atmosphere

Characteristics of the incident protons precipitating into the atmosphere can be derived from measurements by particle detectors on board satellites or rockets. Because of wave-particle interaction and convection processes in the magnetosphere, the keV auroral protons must be measured at the top of the atmosphere, below 1000 km. They are measured routinely by the National Oceanic and Atmospheric Administration/Polar-orbiting Operational Environmental Satellite (NOAA/POES) and Defense Meteorological Satellite Program (DMSP) polar-orbiting satellites at $\sim$ 850 km altitude. Proton spectra observed in the auroral nightside ovals derived from NOAA 6 in the 300 eV - 20 keV energy range and from DMSP satellite in the 50 eV - 32 keV energy range are presented by *Basu et al.* [this issue] and by *Lummerzheim et al.* [this issue], respectively. In the keV range the proton spectra often follow a Maxwellian distribution relatively well. At higher energies (typically above 20 keV) the assumption of a Maxwellian distribution underestimates the high-energy tail that is observed, which seems to follow a power law [*Basu et al.*, this issue; *Galand et al.*, this issue]. Solar MeV protons, with direct access to the polar atmosphere, can be observed from farther away, in the interplanetary medium. To study the effect of the solar protons, *Patterson et al.* [this issue] use particle measurements from the Interplanetary Monitoring Platforms (IMP 8) satellite orbiting around the Earth between 30 and 35 Earth radii. The MeV distribution in energy is shown to be highly variable, but a power law representation can be used. As for the distribution in angle, the intense ion fluxes at high magnetic latitudes are isotropic over the downward hemisphere [*Basu et al.*, this issue; *Galand and Richmond*, this issue; *Jordanova et al.*, this issue], whereas the midlatitude ions from the ring current have more anisotropic fluxes [*Jordanova et al.*, this issue].

From the satellite particle measurements, statistical patterns of the proton characteristics can be obtained. The Air Force Research Laboratory's auroral model uses DMSP particle data as a function of the magnetic index Kp, as discussed by *Galand et al.* [this issue]. The general morphology of the particle precipitation can be inferred from these patterns. On average, the proton energy flux represents $\sim 15\%$ of that of electrons. However, as the proton and electron ovals are shifted, at given locations and times the incident proton particle energy can dominate. It is especially true at the equatorward part of the afternoon and evening auroral ovals [*Galand et al.*, this issue; *Lummerzheim et al.*, this issue]. The patterns of the incident particle characteristics are used to infer the particle-induced perturbations in the atmosphere. One should keep in mind that energetic protons ionize more efficiently than electrons do, as their energy loss per electron produced is less compared with that of electrons [*Galand and Richmond*, this issue]. In regions where most of the energy is carried by protons or where electron precipitation is characterized by a low mean energy, the effect of proton precipitation on ionospheric conductances can be large [*Galand et al.*, this issue].

Measurements are not the only way to get information about the origin and characteristics of incident protons. *Jordanova et al.* [this issue] present a theoretical study of ion precipitation from the ring current, using a kinetic drift-loss model. Proton fluxes are intensified during the main phase of a magnetic storm. The ion precipitation occurs mainly near the plasmapause, within a region of maximum wave excitation. Such a study provides a global view of proton precipitation morphology at midlatitudes and is expected to benefit from new data from the IMAGE and TIMED satellites.

3. Indirect Measurements of Proton Precipitation: H Emissions

Historically, the existence of proton precipitation in the auroral regions was first inferred from ground-based observations of Doppler-shifted hydrogen Balmer series emissions [*Vegard*, 1948; *Meinel*, 1951]. The H lines are emitted by the energetic H atoms produced inside the proton beam and excited through collisions with ambient neutrals. These Doppler-shifted lines are a unique signature of proton precipitation.

3.1. From the Ground

Two H emission lines can be observed from the ground: H_α (656.3 nm) and H_β (486.1 nm) of the Balmer series. However, even though the H_α line is brighter, the close spectral proximity to the bright N_2(1P) emission makes it difficult to obtain clean line profiles. As a result, the H_β line is commonly selected for observations [*Deehr and Lummerzheim*, this issue; *Lummerzheim and Galand*, this issue; *Takahashi and Fukunishi*, this issue].

Lummerzheim and Galand [this issue] use a spectrometer with high spectral resolution to observe H emission Doppler profiles along the magnetic zenith at Poker Flat, Alaska, in the night sector. They use a proton transport model to analyze the data. They demonstrate that the observed red-shifted wing of the line profile has its origin in the aurora and is predicted by the model when collisional angular redistribution of the hydrogen/proton flux is included. They also investigate ways to infer information about the incident protons from the optical measurements. They show that the shape of the blue-shifted wing is a suitable indicator of the mean energy. Such an analysis can be applied to determine the effect of protons, as a source of ionization and heating, in the atmosphere.

H emissions, signatures of proton aurora, along with other auroral emissions have also been used to probe magnetospheric processes. Their observations allow an investigation of proton and electron auroral dynamics during magnetospheric substorms. With this goal, *Deehr and Lummerzheim* [this issue] use meridian-scanning photometers measuring H_β, oxygen lines, and nitrogen bands and an all-sky unfiltered imager at Poker Flat, Alaska. *Takahashi and Fukunishi* [this issue] use a monochromatic all-sky imaging system to obtain images at H_β emission line and its background. In addition, they use a tilting-filter photometer to get Doppler profiles of proton aurora in the magnetic zenith direction with high time resolution. Observations with these instruments were gathered at Syowa station, Antarctica. Among other characteristics, both studies show the expansion poleward of the proton aurora after the onset of the substorm.

3.2. From Space

In addition to the H Balmer lines, it is possible to observe the ultraviolet (UV) H Lyman$_\alpha$ line (121.6 nm) from space. For the first time, *Strickland et al.* [this issue] present an analysis of H lines and nitrogen bands observed during strong proton precipitation with soft electron precipitation. These emissions were recorded from the UV and visible spectrometric imagers on the Midcourse Space Experiment (MSX) satellite. Using results from an electron/proton transport code, calculations are performed to estimate the strength of precipitation - after having removed the solar component - to determine how well the model reproduced the relative brightness of the H emissions and other auroral emissions. Good agreement was found and the general morphology of proton and electron aurora is discussed.

4. Modeling: Proton Transport in the Atmosphere

The interaction of energetic protons and H atoms with the atmosphere can be described by different methods [*Basu et al.*, this issue]. The most comprehensive treatments use either the solution of the Boltzmann equations [*Basu et al.*, this issue] or the Monte Carlo method [*Solomon*, this issue]. A steady state situation is a common assumption. The model inputs are typically the incident proton flux at the top of the atmosphere, the densities of the atmospheric neutrals, and the cross sections associated with the different collisions. The proton and H atom fluxes are computed as a function of altitude, energy, and pitch angle. Integrated quantities can then be derived, such as the electron and ion production rates, the emission rates, or the Doppler profiles of H emissions. Comparison of the energy degradation included in the different models has been successfully performed [*Basu et al.*, this issue; *Solomon*, this issue], as well as direct comparison of the computed particle flux with rocket measurements, as mentioned by *Galand and Richmond* [this issue]. Although the validation of models is a needed step, it is not the main purpose, since these models are mainly used for understanding the physics of proton aurora.

Angular redistributions of particles by magnetic and collisional processes have been studied using such models [*Basu et al.*, this issue]. Comparison of model outputs with H emission observations has shown that the red wing of the H Doppler profile is induced by the upward H atoms redistributed through collisions [*Lummerzheim and Galand*, this issue].

Auroral emissions are induced not only by proton precipitation but also by proto-electrons produced inside the proton beam. The OI(630 nm) red line is a very good illustration, since it is produced from the $O(^1D)$ state which is dominantly excited by the proto-electrons in a proton aurora [*Lummerzheim et al.*, this issue]. In addition, proton precipitation often occurs along with electron precipitation, another source of auroral emissions. As a result, a coupled electron-proton-H atom transport code is needed for the analysis of auroral emissions [*Basu et al.*, this issue; *Strickland et al.*, this issue]. As shown by *Solomon* [this issue], such a coupled code is also needed to derive the electron production rate induced by very energetic protons.

For global studies such comprehensive proton transport codes are too time-consuming. As a consequence, fast computational schemes must be derived to include the effect of protons in global models, such as the General Circulation Models (GCMs) [*Galand et al.*, this issue], or to get a quick estimate of physical quantities, such as conductances, over the high-latitude regions [*Galand and Richmond*, this issue; *Galand et al.*, this issue]. When integrated over the entire hemisphere, the influence of protons as a source of ionization is modest. However, regionally, protons can have a significant effect on atmospheric quantities, such as conductances and neutral winds [*Galand et al.*, this issue].

5. Coordinated Experiments

Such experiments concern observations from the ground and/or from space, providing information on different aspects of the same proton aurora. Typically, measurements of the incident proton fluxes and of one of the perturbed atmospheric quantities are gathered. Using modeling to compare two or more measurements, the influence of protons on the atmosphere can be studied.

Combined experiments between particle detectors on board a polar-orbiting satellite and an incoherent scatter radar on the ground provide data of the incident particle fluxes and of the electron density profile produced by the precipitation, respectively. The analysis of such data with a proton/electron transport code has shown that at the equatorward part of the auroral oval before midnight, protons can represent the major source of ionization of the E region (see references in the work of *Basu et al.* [this issue] and *Galand and Richmond* [this issue]).

Lummerzheim et al. [this issue] have compared O I red line observations from a tomographic imaging chain with particle fluxes acquired from a polar-orbiting satellite. Using a coupled electron/proton transport code to analyze the data they show that the unusual low-altitude peak of the red emission observed from ground is produced entirely by proton precipitation, the major particle energy source around the time period and in the region of the strong red aurora.

Finally, *Patterson et al.* [this issue] have combined MeV proton measurements obtained from space with Relative Ionospheric Opacity Meter using Extra Terrestrial Electromagnetic Radiation (RIOMETER) data from ground providing information on the polar cap absorption of cosmic radio noise. During significant solar particle events, protons, especially of energies below 10 MeV, are the primary contributors to PCAs. In addition, *Patterson et al.* [this issue] explain how such observations can be used to infer the effective ion-electron recombination coefficients in the ionosphere, coefficients whose values are subject to large uncertainties.

6. Discussion

In section 2 we have focused on the characteristics of the incident protons. Ion detectors on board satellites usually have no mass discrimination, so all the ions are assumed to be protons. Ion detectors also usually have no charge separation, so they make no distinction between ions and energetic atoms. In the ring current, *Jordanova et al.* [this issue] suggest abundances of 30% of O^+ compared to H^+ and 4% of He^+ compared to O^+, at the peak of the studied storm. At times, O^+ precipitation is significant at some locations. It should be noted that the interaction of O^+ with the atmosphere is very different compared to H^+. The oxygen ions do not ionize efficiently; instead, they mainly heat the neutral atmosphere [*Rees*, 1989].

In section 3, H emissions have been used as signatures of proton precipitation [*Deehr and Lummerzheim*, this issue; *Lummerzheim and Galand*, this issue; *Takahashi and Fukunishi*, this issue; and *Strickland et al.*, this issue]. *Share and Murphy* [this issue] show that gamma rays can also be used to track energetic protons, especially solar MeV protons. The quiescent atmospheric gamma-ray spectrum induced by cosmic rays is very different compared to the spectrum produced by solar energetic protons. From the Solar Maximum Mission (SMM) gamma-ray spectrometer data, these authors show how information on the energetic protons from an intense solar particle event can be inferred.

Unlike particle detectors providing data only along the track of the satellite, imagers of auroral emissions can give a global picture of auroral activity. The associated data analysis yields the particle input over the high-latitude regions during a magnetic storm. First attempts are very promising [*Strickland et al.*, this issue]. With very recent and future missions (IMAGE, TIMED, future DMSP, and NPOESS), H emission observation will increase in the years ahead to yield more pictures of the particle input over the globe.

In section 4, proton transport models have been discussed [*Basu et al.*, this issue; *Solomon*, this issue; *Galand and Richmond*, this issue; *Galand et al.*, this issue]. Our ability to accurately model the proton aurora is now mainly limited by the uncertainties in the input data [*Basu et al.*, this issue]: cross sections, phase function, atmospheric neutral model, and characteristics of the incident proton flux. As a consequence, proton modeling relies strongly on future laboratory experiment and in situ observations. As shown by *Basu et al.* [this issue], integrated quantities such as the electron production rate are sensitive to the high-energy tail of the proton spectrum. The high-energy tail of the spectra (typically above 20 keV) should receive particular attention to improve the modeling results.

Section 5 deals with coordinated experiments [*Basu et al.*, this issue; *Lummerzheim et al.*, this issue; *Patterson et al.*, this issue]. The main issue in such experiments is the question of the "same" aurora being observed by different instruments. In addition to the uncertainty of the configuration of the magnetic field lines along which energetic protons precipitate, it is very difficult to get exactly coordinated observations in time and in space. One solution to this problem is to have all the needed instruments, such as a particle detector and an H emission spectrometer, on board the same satellite. This will soon be possible on the future DMSP and NPOESS missions.

A subject that we did not discuss during the CEDAR 99 workshop, but that we are very happy to include in this special section, is energetic proton and H atom precipitation occurring on extraterrestrial bodies. *Kallio and Barabash* [this issue] present a study concerning the influence of an intensive flux of precipitating energetic hydrogen atoms on the Martian atmosphere. Atmospheric effects of these particles are a manifestation of the interaction between the solar wind and the planetary atmosphere. The theoretical work presented is based on a Monte Carlo simulation model and shows that the effect of energetic H atoms is small compared to that of the extreme ultraviolet (EUV) radiation, but it is comparable to or larger than effects of H^+ and O^+ precipitation.

The different subjects discussed in this paper are all interconnected. For example, models depend on the incident proton flux at the top of the atmosphere, whereas they are needed for analyzing auroral emissions. Study of magnetospheric processes can be aided by H emission analysis. Moreover, the experience acquired from proton aurora on Earth and the diversity of sources of precipitation encountered in the solar system should provide new insights for both the terrestrial and planetology communities. Collaborations between scientists involved in these different issues is crucial for a better understanding of proton aurora. It is hoped that this special section will strengthen these links.

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