On deriving incident auroral particle fluxes in the daytime using combined ground-based optical and radar measurements

Duggirala Pallamraju,¹ Supriya Chakrabarti,² and Stanley C. Solomon³

Received 15 July 2010; revised 20 January 2011; accepted 24 January 2011; published 13 April 2011.

[1] Particle energies and fluxes have predominantly been measured from instruments onboard satellites. In this study, we use daytime ground-based oxygen redline emission measurements, along with the ionospheric electron density, and electron temperature profiles measured from the incoherent scatter radar, and a physics-based modeling approach to derive the energy and flux of particles incident over Boston during the storm of 30 October 2003. We find that the characteristic energy and the associated flux vary between 0.07–5.7 keV and 0.5–130 mW m⁻², respectively, during the intense magnetic disturbance that brought aurora to midlatitudes. Such an approach not only offers another method to estimate the incident particle energies and fluxes but also enhances our understanding on the channels of energy deposition in the upper atmospheric region, especially during magnetic disturbances, about which database is poor.


1. Introduction

[2] Auroral emissions are a result of interaction of particles of solar wind origin with the constituents of the high-latitude upper atmosphere. Estimation of the energy inputs into the upper atmosphere is essential not only to quantify the energy budget into this region but also to understand the coupling between the atmospheric regions during space weather events when the energy flux shows significant spatial and temporal variation. Heating of the high-latitude upper atmosphere due to such particles of high energies can be, at times, equal to that of the solar EUV over low latitudes [Mayer et al., 1978]. Particle fluxes and particle energy spectra have been measured both by direct and indirect methods. Direct measurement of incident energy spectra and fluxes can be made by satellite-borne particle detectors (for example, DMSP [Hardy et al., 1985]). Particle energies and fluxes have been inferred indirectly by the effect they produce on auroral optical emissions from various species at different wavelengths due to the varying excitation energies required for different emissions. Ground-based measurements of the relative brightness of auroral N₂ 1NG and H₉ emissions were used to infer whether the precipitating flux was dominated by protons or by electrons [Vallance-Jones et al., 1982; Hecht et al., 2006]. In the case of electron influx, whether the precipitation was due to soft (<600 eV) or energetic particles (order of a few keV) was determined using the ratios of oxygen redline (6300 Å) to greenline (5577 Å) auroral emission intensity [e.g., Rees and Luckey, 1974; Vallance-Jones, 1974]. Further, derivation of proton energies was attempted using the ratios of H₉ (6563 Å) and H₅ (4861 Å) emissions [e.g., Vallance-Jones et al., 1982; Galand et al., 2004]. Using ratios at extreme ultraviolet emissions measured from onboard satellites, incident particle fluxes have been estimated (e.g., GUVI [Paxton et al., 1999]). There exist physics based model estimates [e.g., Rees, 1963; Meier et al., 1989], and laboratory experiments [Cohn and Caledonia, 1970; Barrett and Hays, 1976] to quantify the energies of particles that enter into the Earth’s upper atmosphere. Estimation of energies and fluxes using radar-based inversion techniques are quite involved and even when such is possible, they are restricted to particle energies at keV range and beyond [Semeter and Kamalabadi, 2005]. Janhunen [2001] presented a method for reconstructing the precipitating electron flux from a set of multiwavelength digital all-sky auroral images, which involves solving a large linear inversion problem. A limitation is that arcs that are significantly off-zenith and are viewed sideways by only one all-sky camera station are smeared out.

[3] Generally, precipitation of particles of solar wind origin occurs along the open geomagnetic field lines at high latitudes. During the severe geomagnetic storm of 30 October 2003, famously called the Halloween storm, long periods of strong Bz south conditions enabled magnetic reconnection further equatorward than normal regions. Due to this equatorward movement of the reconnection region during this event, the intensity peak of the outer radiation belt electron moved from its nominal position of L ≈ 4 to L ≈ 2.5 in a day [Li et al., 2009]. These conditions facilitated the
entry of particles to middle-latitude locations, such as Boston (42.20°N, 71.05°W; 48.3° magnetic latitude (MLAT)), which resulted in aurora in the daytime over Boston [Pallamraju and Chakrabarti, 2005], and severe Total Electron Content (TEC) fluctuations [Basu et al., 2005; Mannucci et al., 2005], etc. among other effects. There have been only a few studies (e.g., on board ISIS satellite) wherein simultaneous measurements of incident particles and optical measurements were carried out which brought out an empirical relationship between the production efficiency of the auroral redline emission with respect to the particle precipitation [Shepherd et al., 1980]. In this paper, we present the results obtained on the magnitude of the electron energy fluxes that were incident over Boston during daytime using combined optical, radar, and physics based modeling work. We estimate the particle energy flux by attributing to it the excess OI 6300 Å optical emissions measured when compared to the model values of dayglow emissions.

2. Data Description

[4] The daytime optical redline emission measurements have been carried out by the High Resolution Imaging Spectrograph using echelle grating (HIRISE) instrument, which is a high spectral resolution (0.12 Å at 6300 Å) spectrograph capable of observations over varying fields of view from 8° to 180°. The high spectral resolution sky spectra obtained by HIRISE are compared with a reference solar spectrum that is convolved with the HIRISE instrument function. Their difference obtained in the wavelength region of interest yields information on the dayglow emission and scattering (Ring effect contributions). The details of measurement technique, removal of the Ring effect, and a review of results obtained by this technique have been reported earlier [Pallamraju et al., 2000, 2002, 2004, 2010; Pallamraju and Chakrabarti, 2006].

[5] In the present work, the daytime optical redline emission measurements on 30 October 2003 over a midlatitude location (Boston) are discussed. The solar zenith angle (SZA) varied from 70° to 115° during the time interval (1415–1900 LT) of auroral observations over Boston. The daytime auroral emissions were so intense that they filled in the 6300 Å Fraunhofer absorption line and stood out as a bright emission in the raw spectral image of HIRISE as can be seen in Figure 1. Figure 1 (top) shows the sky brightness as a function of wavelength. Several Fraunhofer absorption features can be seen. The enhancement due to redline emissions can be clearly noted at 6300.3 Å. Figure 1 (bottom) shows the difference obtained by comparing the day sky spectrum shown in Figure 1 (top) with the solar spectrum. The emission magnitude is estimated to be 38 kR at this time. This intensity is six times larger than the normal daytime airglow emission rate for that day. During this time the SZA was 74° and the solar scattered background continuum was $4 \times 10^6$ Rayleighs Å$^{-1}$. Such large enhancement in the emission intensity as reported by Pallamraju and Chakrabarti [2005] was due to the daytime aurora generated in response to an X-class coronal mass ejection on the sun. [6] The optical measurements obtained at different times of this day have been compared with the estimates of the semi-empirical dayglow model emissions [Zhang and Shepherd, 2004], and with the GLOW model obtained using the Millstone Hill radar (42.6°N, 71.5°W; 53.4°MLAT) measured $N_e$, and $T_e$, profiles as inputs. In this experiment the data cadence of optical emissions is about 5 min and that of the radar data is 15 to 20 min. As shown in Figure 3a of Pallamraju and Chakrabarti [2005], and reproduced here as Figure 2, the magnitude of model emissions agreed extremely well with the measurements during the period when there was no aurora (during time interval T1). However, only the temporal behavior between the model and the observations (and not their emission brightness magnitudes) matched during aurora (interval T2). The measured daytime redline emissions were much higher than the modeled emission intensities after 1400 LT (during the time interval T2). This is because the model calculations did not consider the contribution to the

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (top) The day sky spectrum (at 1509 LT and at a solar zenith angle of 74°) obtained by HIRISE from Boston on 30 October 2003 during the Halloween storm. Several Fraunhofer absorption lines can be seen. It can be noted that the daytime redline (OI 6300.3 Å) auroral emissions show up clearly over and above the background continuum. (bottom) A one Angstrom wavelength range of this data showing the details of the auroral emissions.
oxygen emissions due to the incident fluxes. The model emissions being larger than the measurements (without considering the contribution due to the fluxes of energetic particle precipitation) during 1800–1900 LT indicates that there are significant structures and dynamical variation in the aurora between zenith (optical emissions over Boston) and the ISR location (north of Boston), that are separated by around 70 km (the radar measurements are from a location toward northwest of the optical site). The present paper describes the approach by which incident particle energies and fluxes in the interval T2 have been estimated.

3. Data Analysis and Results

The difference between the measured and the modeled dayglow emissions that can be seen in Figure 2 is now assumed to be only due to precipitating particles as all other contributions have been considered in the model calculations. To estimate the incident particle precipitations it is required to know their characteristic energy $E_0$ and the particle flux at that energy $E_0$. From the Millstone Hill radar measured electron density profiles we obtain the peak height, $h_{\text{max}}$, of the ionospheric F layer at that time. We assume that monoenergetic electrons of energy $E_0$ are responsible for producing the ionization, which results in an observed $h_{\text{max}}$ in the electron density profile. From the vertical profiles of ionization production rate for different characteristic energies as given by Rees [1963], a characteristic energy $E_0$ is obtained for the measured $h_{\text{max}}$ of electron density profiles at a given time.

Figure 3 shows the variation of $h_{\text{max}}$ with time. Superposed on this plot is the variation of SZA with time. As the SZA increases, the solar ionizing flux must traverse a larger optical path and therefore, the peak height of ionization moves upward. Further, the ionization in the E and the lower F regions recombines quickly due to larger collision frequency with the neutrals. These two effects combined result in an apparent rise in the peak altitude of the F region at the sunset time. Thus, it can be seen that during the time interval T1, a rise in the $h_{\text{max}}$ (until about 1400 LT) is consistent with the increase in the SZA. During time interval T2, however, variation in $h_{\text{max}}$ is erratic due most likely to the incidence of particles of varying energies during aurora. The greater the energy of the incident electrons, the deeper will be their penetration depth, and therefore the $h_{\text{max}}$ is shifted to lower altitudes [Rees, 1963]. In general, $h_{\text{max}}$ of the ionosphere is affected by the changes in the electric
fields, winds, and temperatures. For this severe storm prompt penetration electric fields have been reported over low/ equatorial latitudes based on data from digital ionosondes [Abdu et al., 2008] and DMSP satellites [Mannucci et al., 2005]. Their effect, however, is largest over magnetic equator [Tsurutani et al., 2008] and has a decreasing trend with increasing latitude. While Abdu et al. [2008] had shown the rise of the F layer over Sao Luis, Brazil and Jicamarca Peru, to over 1000 and 800 km, respectively, the Digisonde data from Millstone Hill, MA USA (closer to the location of optical measurements) showed no trace of echo after 1415 LT indicating absorption of radio waves by the excess ionization created due to precipitation of particles (source: Digital Ionogram Database website). The Millstone Hill incoherent scatter radar data was used for the present analysis. It can be noted from Figure 3 that the peak production in ionization is at around 150 km during several occasions (after 1430 LT) due to particle precipitation. Also, in Figure 3 it can be noted that during 1445–1530 LT, the height of peak production in ionization was significantly lower (~320 km) than that at 1415 LT (~480 km). Such lower heights of ionization (at such large solar zenith angles) are only possible if there is an influx of precipitating particles, as other effects such as increase in electric fields and temperatures would mainly contribute to an increase in the $h_{\text{max}}$. Although we do not discount the role played by prompt penetration electric field in the modification of $h_{\text{max}}$, based on the above arguments, we conclude that the predominant factor governing the height of the ionosphere over middle latitudes during this epoch is the influx of energetic precipitating particles.

As mentioned above, from the data of $h_{\text{max}}$, $E_0$ is obtained assuming a Maxwellian distribution in electrons that produced the peak in the ionization at $h_{\text{max}}$ as observed by the Millstone Hill radar. Figure 4a shows the $E_0$ obtained during 1400–1700 LT by the ground-based data (plus symbol). The energy $E_0$ is used as input to the GLOW model [Solomon et al., 1988; Solomon and Abreu, 1989; Bailey et al., 2002]. The modeling approach is based on a two-stream radiative transfer method introduced by Nagy and Banks [1970]. The cascade of electrons from high to low energies is computed by considering the highest-energy electrons first and then solving for successively lower energies until near-thermal levels is reached. The transport of photoelectrons generated by solar extreme ultraviolet irradiance and auroral electrons generated by a primary flux incident at the model upper boundary are computed simultaneously, so that emissions consequent to the combined effects of dayglow and auroral excitation can be calculated. In the present case, using this $E_0$ as input into the GLOW model, the electron flux is iteratively varied and the estimates of the optical emissions are obtained. The flux at which these modeled emissions match with the measurement is taken to represent the magnitude of the electron flux $Q_0$ (at the characteristic energy $E_0$) at that time. Figure 4b shows the energy flux $Q_0$ as obtained by our analysis, as described above, at different times (plus symbol). We compare our results of $E_0$ and $Q_0$ obtained with those derived by the GUVI measurements of ultraviolet emissions emanating from the upper atmosphere in Figure 4. These estimates are obtained in a similar fashion to ours but by using the UV emissions (OI 1304 Å for $E_0$ and N2 Lyman–Birge–Hopfield band of 1400–1500 Å regions) measured from a space-based platform (triangles) [Paxton et al., 1999]. It may be noted that the estimates from GUVI are at 50° MLAT, which is at the equatorward boundary for the energy estimates by these measurements. The time duration for GUVI data coincides with our measurements for only a short duration (1430 to 1530 LT) in this period of aurora over Boston. It may be noted that the $E_0$ obtained during 1430 to 1530 LT...
Figure 5. (a) \( Q_0 \) estimated in the present work (plus symbol) using as inputs a Maxwellian distribution of the flux at \( E_0 \) into the GLOW model. The \( Q_0 \) estimated using the Meier et al. [1989] calculations (RM89) are also shown (diamonds). It can be noted that the agreement between these two is better than the comparison between HIRISE and GUVI derived \( Q_0 \) as shown in Figure 4b. (b) The redline column emission rates using the RM89 estimated \( Q_0 \) (diamonds) is compared along with the difference between the observed and modeled emissions (plus symbol), which shows a very good agreement.

shows an exact match between the ground and space based estimates (Figure 4a). With regard to \( Q_0 \) as well, the magnitudes between these two estimates show a very good agreement during 1500–1530 LT, in spite of the differences with regard to locations and measurement techniques. There are several uncertainties, both in terms of the sensitivity of the UV and visible emissions to the incident energy flux, location of measurements, sensitivities of both the instruments, etc. Under this background, it can be noted that there is a good agreement between the magnitudes (both in \( E_0 \) and \( Q_0 \)) derived by GUVI measurements and the ones derived from our analysis.

In order to carry out further validation of the results obtained by our method, we compared them with those of the model study on the sensitivity of the redline emission rate to the incident particle flux, as presented by Meier et al. [1989] (represented as RM89). Meier et al. [1989] presented the modeled redline emission rates as a function of characteristic energy \( E_0 \) for a 1 mW m\(^{-2}\) flux of particles. Figure 5a shows the \( Q_0 \) derived based on our measurements (plus symbol). Based on the \( E_0 \) obtained using the \( h_{\text{max}} \) data as shown in Figure 4a, we estimated the redline column emission rates for a 1 mW m\(^{-2}\) flux given by RM89 calculations. This estimate was used to scale the difference of emissions with and without particle fluxes in the GLOW model emissions to obtain an independent measure on the magnitude of \( Q_0 \) at each of the times when the observed emissions were greater than the model emissions (as shown in Figure 2). The \( Q_0 \) values so derived are represented in the Figure 5a (diamonds). One can note that the agreement here is much better (within 20%-30%) as compared to the one obtained between our optical measurements and those from GUVI as shown in Figure 4b. Further, the RM89 derived \( Q_0 \) values were used to obtain the column emission rates and are compared with the difference in emissions, between the measured and physics based modeled ones and are depicted in Figure 5b. It can be seen that many a times these two are in excellent agreement. The differences between them on some occasions could be possibly due to uncertainties in the estimation of correct \( E_0 \). The height resolution for the ISR measurement was 18 km. As discussed in greater detail in section 4, \( E_0 \) is sensitive to \( h_{\text{max}} \). Thus, it is expected that a better height resolution in obtaining \( h_{\text{max}} \) will reduce the uncertainty in obtaining \( E_0 \) and at the same time enable obtaining a more accurate estimate of \( Q_0 \).

Figure 6 shows the modeled redline emissions after considering the particle energy flux into the GLOW model during 1400–1900 LT for the duration T2. It is apparent that this modeled emissions rates now match well with the measurements as compared to Figure 2 above. As mentioned in section 2, the optical instrument is an imaging spectrograph, which means that the data from different pixels on the CCD correspond to different view angles in sky along the orientation of the slit. Measured optical emission intensity toward a station north of Boston (obtained from the same instrument, but by binning the pixels on the CCD differently) is also depicted in Figure 6 to show the dynamical state of the auroral movement during that event. Here, the solid line shows the emissions over zenith while the dashed line indicates the emission intensities toward magnetic north, which are separated by about 0.5° in latitude assuming an emission altitude of 230 km. The dotted line shows the modeled emissions using the radar data, which as mentioned earlier, were taken from a location northwest of the optical site. The increase in the model emissions at around 1800 LT are earlier by about 40 min than the measurements (dashed line). As the measurement site is about 50 km east of the radar site, the inferred speed of this structure is around 75 km h\(^{-1}\) eastward. The relatively poorer data cadence of the radar measurements as compared to the optical data prevents a more detailed comparison of the temporal variability in the structure of emissions. Before 1800 LT there have been simultaneous excursions in the measured and modeled emissions. Thus, it can be
inferred that before 1800 LT the auroral structure was relatively larger in size, of at least about 80 km in diameter, as it encompasses both the radar and the optical sites. Furthermore, the emission variability in the zenith (solid line) between 1712 and 1812 LT and that toward the north (dashed line) between 1812 and 1900 LT seems similar. This indicates that the structure is moving northward at a speed of 44 km h\(^{-1}\). In combination with this northward movement and the eastward movement in structure as described above, it can be inferred that there is a net north-east movement in the auroral structure during this time.

### 4. Discussion

[12] The results obtained on the particle energy and flux using a combined optical, radio, and physics based modeling approach has been presented. The requirement for this approach is the presence of near collocated ionospheric and optical measurements. As the \(E_0\) is derived based on the value of the peak height of the electron density, the uncertainty in our result on the estimation in particle characteristics is dependent on the accuracy of which \(h_{\text{max}}\) is determined. It can be seen from the result reported by Rees [1963], that there is an exponential rise in the characteristic energy of the particles that penetrate deeper into the atmosphere versus those that are absorbed at higher altitudes (for example, 5.6 keV at 119 km, 1.65 keV at 147 km, and 0.4 keV at 270 km). Therefore, the uncertainty in obtaining \(E_0\) is significantly smaller at higher altitudes than those at lower altitudes. Given the uncertainty in the peak height estimation of 18 km, the uncertainty in \(E_0\) can be 60%–80% and around 20% for precipitating particles of high (~5 keV) and low (~0.4 keV) energies, respectively. Considering an average uncertainty in \(E_0\) to be ~40% the relative variation in the derived fluxes are at least as much (as shown in Figures 4 and 5). It should however be noted that the redline production efficiency is high for low-energy particle precipitation. Thus, for a lower \(E_0\) a smaller flux of incident particles will result in the same emission intensities as larger flux at higher characteristic energy, \(E_0\) [Meier et al., 1989]. It is known that the redline emission is sensitive to the variation in the neutral density and composition [Strickland et al., 1989]. It has also been shown recently [Hecht et al., 2008] that there could be an error of around 15% or more in the MSIS neutral densities, especially during severe geomagnetic storm conditions. However, as the uncertainties in the \(E_0\) and \(Q_0\) are greater, it is assumed that the variation in the neutral density during this event as described by the MSIS model would not significantly alter the results.

### 5. Summary

[13] In this work we present the results obtained on the characteristic energies and particle fluxes incident over Boston during the magnetic storm of 30 October 2003. We use daytime/twilighttime ground-based oxygen redline emissions along with the ionospheric electron density and electron temperature profiles from the incoherent scatter radar, and forward modeling to derive this information on the incident particle energies and fluxes. Assuming a Maxwellian distribution of incident particles we estimated the characteristic energy based on the Millstone Hill radar measured height of the F layer, which varies in time. We vary the energy flux for a given characteristic energy into the GLOW model to

Figure 6. Modeled GLOW emissions taking into account the particle flux incident during this event (dotted line) for the duration T2 (1400–1900 LT) are shown. Measured optical redline emissions intensities over zenith (solid line) and north of Boston (dashed line) show a good match with the modeled emissions. It can be noted that the emission variability over zenith during 1712 to 1812 LT leads that of a similar variation in the north during 1812 to 1900 LT. Further, the modeled emissions using as inputs the radar measured ionospheric parameters at 1800 LT leads that over the measured emissions northward of zenith. As the radar site is northwest of the optical site, the above two observations indicate that there is a northwest movement in the auroral structure.
match with the measured intensity of auroral emissions in the daytime to obtain an estimate on the particle flux incident at that time. We find that the characteristic energy and flux varied between 0.07 and 5.7 keV and 0.5 to 130 mW m⁻², respectively, during the period of intense magnetic disturbance, which brought the aurora to middle latitudes during the daytime. Our results agree well with the physics based model calculations reported by Meier et al. [1989] and the GUVI based measurements obtained from a slightly northern location to the optical measurements. This technique presents a great potential in obtaining information on particle fluxes incident into the Earth’s atmosphere during daytime at a high temporal resolution.

[14] Acknowledgments. We thank John Foster for making the ISR electron density and temperatures data available to us. We thank Larry Paxton for the GUVI data. Critical comments by the reviewer are duly acknowledged. The work at BU was supported by NASA grant NNX06C04G. The work at NCAR is supported by NASA grant NNX08AQ11G. NCAR is sponsored by the NSF. This work is supported by Department of Space, Government of India.

[15] Robert Lysak thanks the reviewers for their assistance in evaluating this paper.

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S. Chakrabarti, Center for Space Physics, Boston University, Boston, MA 02215, USA.

D. Pallamraju, Space and Atmospheric Sciences Division, Physical Research Laboratory, Narvrangpura, Ahmedabad, Gujarat, 380 009, India. (rajus@prl.res.in)

S. C. Solomon, National Center for Atmospheric Research, High Altitude Observatory, Boulder, CO 80307, USA.