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A multiwavelength investigation of the Ring effect in the day sky spectrum

D. Pallamraju, J. Baumgardner, and S. Chakrabarti

Center for Space Physics, Boston University, Boston, Massachusetts, USA

Abstract. Ring effect refers to the 'filling-in' of the Fraunhofer absorption lines in the day sky spectrum as compared to the solar spectrum. Rotational Raman scattering is believed to be the main cause for this excess in the sky spectrum. Earlier measurements showed contradictory behavior of this effect with solar zenith angle and wavelength. It is important to take proper account of this effect as it otherwise results in overestimating the dayglow emission intensities and underestimating the number densities of atmospheric trace gases. The present study details the results obtained from a simultaneous 11-wavelength investigation carried out using a newly built daytime spectrograph. This data demonstrates that the absorption line strength (normalized depth × half width) has a major control on the Ring effect contribution irrespective of the solar zenith angle and the wavelength.

Introduction

The spectra of the sun and the day sky obtained from the ground are different in terms of the depths of the Fraunhofer absorption lines. For non-telluric lines, it has been observed that the absorption lines in the sky spectra are 'filled-in' as compared to those of the sun and this feature is referred to as the Ring effect [*Grainger and Ring*, 1962]. Ring effect has also been observed in the scattered light from the moon and several planets such as Mars, Jupiter and Uranus (*Cochran et al.,* [1981] and references therein). Several mechanisms, such as aerosol fluorescence [*Noxon and Goody*, 1965], earth's albedo [*Hunten*, 1970], Rotational Raman Scattering (RRS) [*Brinkmann*, 1968] and Rayleigh Brillouin scattering in addition to RRS [*Kattawar et al.*, 1981] have been suggested for this contribution; but RRS is now generally agreed to be the primary source. These above studies found that the absolute Ring effect contribution (REC) varies with Solar Zenith Angle (SZA) and wavelength. Since the background continuum (BC) level also varies with both SZA and wavelength, we compute the Fractional Ring effect (FRE) which is defined as:

$$\mathrm{FRE} = (\mathrm{REC})/(\mathrm{REC}+\mathrm{BC})$$

It is important to know the Ring effect contribution as it otherwise results in the overestimation of the dayglow emission intensities present in the Fraunhofer absorption regions. The Ring effect also reduces the apparent depths of the structured molecular absorption regions, thereby leading to underestimation in the measured column densities of stratospheric trace gases such as, O_3, NO_2, OClO, BrO, etc. [*Fish and Jones*, 1995]. Modeling studies have been attempted to estimate this filling-in amount due to RRS mechanism in order to derive physical parameters such as temperature and pressure at cloud heights and abundances of trace gases [*Joiner et al.*, 1995; *Chance and Spurr*, 1997; *Vountas et al.*, 1997]. Hence it is essential to determine its true behavior so that the Ring effect contribution can be properly accounted for in the experimental and modeling studies.

To understand the variation of the REC with respect to SZA and wavelength, we made comprehensive measurements at 11 wavelengths using a high resolution **H**igh **T**hroughput **I**maging **E**chelle **S**pectrograph (HiTIES), which is capable of making simultaneous measurements at different wavelengths in the visible spectrum [*Chakrabarti*, 1998]. Our measurements revealed for the first time that the FRE has a stronger dependence on the Fraunhofer **absorption line strength** (normalized depth × half width) than either the SZA or the wavelength. This revelation has far reaching consequences, considering the increasing use of ground based instruments for daytime thermospheric emission measurements [*Chakrabarti*, 1998; *Sridharan et al.*, 1999] and techniques from satellites and ground being employed to estimate the abundance of atmospheric trace gases [*Fish and Jones*, 1995; *Joiner et al.*, 1995; *Chance and Spurr*, 1997; *Vountas et al.*, 1997].

Background

Previous ground based measurements of the Ring effect showed inconsistent correlations, both with SZA and wavelength. *Pavlov et al.* [1973], *Barmore* [1975], and *Harrison* [1976] showed an *increase* in the FRE with SZA by a factor of around 2 to 3 from a SZA of 30° to 90°. However, *Noxon and Goody* [1965] and *Harrison and Kendall* [1974] showed a *decrease* in the Ring effect by a factor of ∼2 with SZA (in similar SZA range). *Conde et al.* [1992] found the FRE at 589.3nm to remain nearly constant during the day followed by a steep rise (by a factor of 6) around twilight time. With regard to the variability in wavelength, *Noxon and Goody* [1965] and *Pavlov et al.* [1973] showed a *decrease* of FRE with wavelength while *Harrison and Kendall* [1974] and *Chanin* [1975] showed an *increase* in the FRE with wavelength. In all the above measurements the instrument resolutions were poorer (∼ 0.2-0.4nm vs. 0.012nm) than the present experiment (except for *Chanin* [1975] and *Conde et al.*, [1992]) and were carried out at most four wavelengths. The present high spectral resolution and simultaneous measurements at 11 wavelengths from three distinctly different spectral regions try to offer a plausible explanation to the existing controversies by bringing out the behavior of the Ring effect variability.

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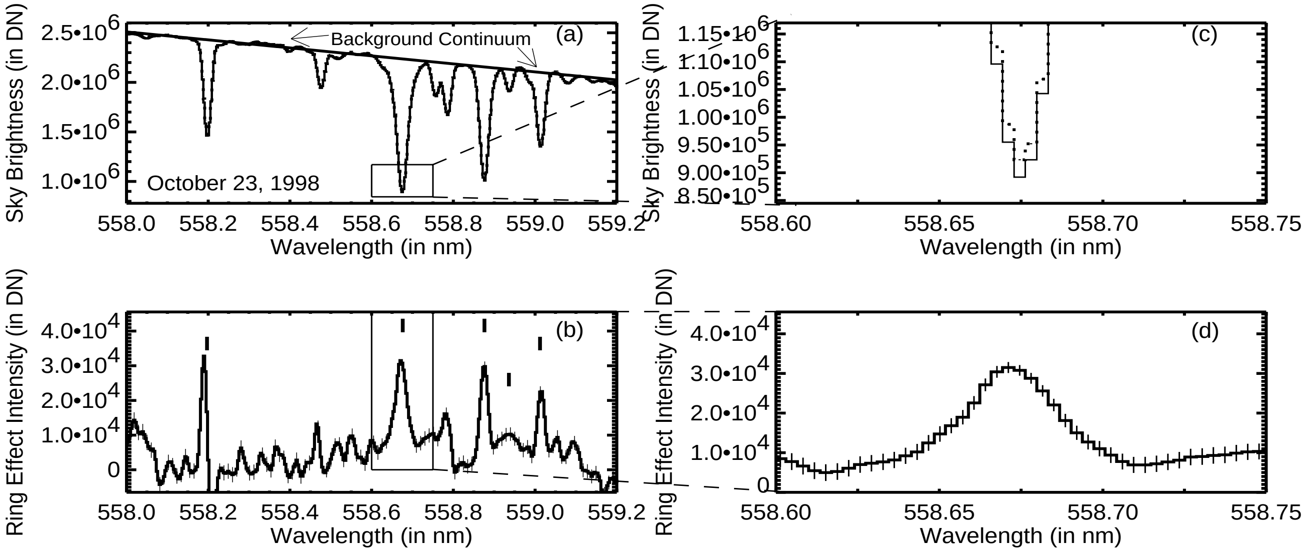

Figure 1. **(a)** Scaled solar spectrum superposed over the sky spectrum (obtained for 100 second exposure) for 558.6nm wavelength panel. The 'neighboring' continuum levels outside the absorption lines under consideration are used to obtain a linear fit for determining the background continuum (BC) level at each wavelength region of interest. The y-axis is expressed in Data Numbers (DN). At this scale the difference is too small to be seen. Their difference, the Ring effect intensity with wavelength, is shown in panel **(b)**. The $\pm 1\sigma$ error bars indicating photon count statistics are also shown. The absorption lines considered for detailed analysis are shown by small vertical lines. The details for one absorption line at 558.676nm, shown as a box in panels **(a)** and **(b)** are blown-up and are shown in panels **(c)** and **(d)**. In panel **(c)**, the sky and the solar spectra are shown by dotted and solid lines respectively. The corresponding Ring effect at this wavelength is shown in panel **(d)** along with the $\pm 1\sigma$ errors.

Technique

The HiTIES instrument is a long slit Echelle spectrograph (slit length of 40mm) that uses a mosaic of filters (rectangular strips of interference filters arranged one next to the other) placed behind the slit for order separation and a 1K x 1K back thinned CCD detector to record the high resolution spectrum. It has a f/11 input optics and attains a dispersion and resolution of 0.004nm/pixel and 0.012nm, respectively at 589.3nm. The procedure to obtain REC is to compare the high resolution solar and sky spectra. The difference between them would yield the REC. It should be kept in mind that neither the solar nor the sky spectra obtained using this instrument are the *true* spectra but are convolutions of the true spectrum with the instrument function. We are able to subtract these two scaled spectra simply because they have been obtained by the same instrument with identical instrumental parameters for both data sets. Three spectral regions around 428.6, 558.6 and 656.0nm have been chosen for the present study. 11 wavelengths have been chosen from these spectral regions after ensuring that none of them consists of any known dayglow emissions, telluric absorption features or 'blend' of two lines.

Several solar spectra are obtained by reflecting direct sunlight on to a thin glass diffuser placed over the entrance slit of the HiTIES. The function of the diffuser is to present an integrated effect of the solar disk on to the slit and to 'spread' the light evenly along the slit. This diffuser is not known to have any small scale spectral properties. The solar spectral images so obtained by HiTIES are averaged after individually correcting them with an averaged dark image obtained for the same duration. Due to the 'mosaic' of filters at the front-end of the instrument, this image consists of sections of different spectral regions along the slit direction. Such an averaged, dark subtracted image is used to obtain a '*standard/reference* solar spectrum' for each of the spectral regions. It is then scaled with the corresponding sky spectra obtained during different times of the day, by a least-square technique to match the continuum. For the present analysis, the sky spectrum is obtained by adding up the brightness values from the spatial bins along the slit to reduce the statistical fluctuations. For a 100 second integration, a typical value of sky brightness is $\sim 2.2\times10^6$ DN (Data Numbers). The errors in the difference between the sky and solar spectra range from 1300-2300 DN depending on the brightness level. The errors in the estimation of the FRE range between 0.1% to 1.2% depending on the strength of the absorption line. Since we use the same instrument for comparing the two spectra and, more importantly, as we are interested in the *relative* Ring effect variations only, the systematic errors, if any, do not seriously affect our results.

Results

The present investigation was carried out from Boston (42.2°N, 71.05°W). Zenith sky measurements were made on clear blue sky days during October- November 1998. Figure 1 shows typical spectra obtained from the 558.6nm region. Panel **a** shows the sky spectrum (dotted line) superposed over the solar spectrum (solid line). A linear fit has been obtained between the continuum regions on either side of the absorption lines under consideration, to estimate the background continuum (BC) at the Fraunhofer absorption wavelength of interest. The difference between these spectra, which represents the Ring effect, is shown in panel **b**. Notice that the filling-in at the wavelengths selected (as marked by small vertical lines in panel **b**) is quite different even though they are separated by a fraction of a nanometer. The details of the filling-in at a typical absorption line at 558.676nm are shown in panels **c** and **d**. The data num-

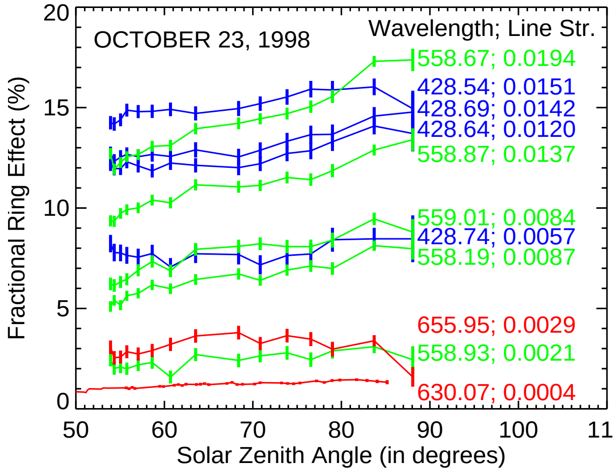

Figure 2. Fractional Ring effect is shown as a function of SZA along with $\pm 1\sigma$ errors. Wavelengths and their absorption line strengths (both in nm) are also listed. Blue, green and red colors represent the wavelengths considered around 428.6, 558.6 and 656.0nm spectral regions respectively. Notice the general increase in the FRE for all wavelengths, with relatively higher increase for absorption line strengths greater than 0.005nm, especially for the 558.6nm panel. (All measurements were obtained on October 23 1998, except for 630.07nm which was obtained on October 6, 1998).

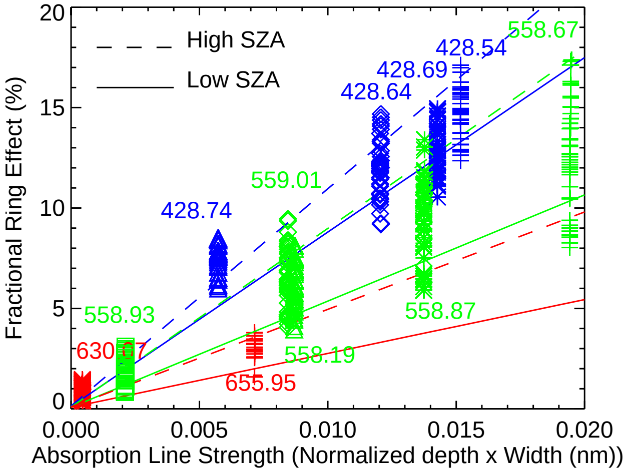

Figure 3. Fractional Ring effect is shown as a function of absorption line strength for three days of available data. It can be seen that the absorption line strength has a greater control on the Ring effect than either the wavelength or the SZA. The vertical spread in data points at each wavelength shows the variations associated with the SZA. Linear least square fitted lines for low (<55°) SZA (solid) and high (>80°) SZA (dashed) for each of the blue, green and red panels are also shown. The linear fits have been made to pass through the origin as there is no Ring effect at the continuum level.

bers under such curves shown in panel **d** are summed-up for the chosen wavelengths to obtain the REC at those regions. FRE calculated for all the 11 chosen wavelengths at different times of the day are shown in figure 2 as a function of SZA for October 23, 1998. Wavelengths from 428.6, 558.6 and 656.0nm regions are shown in blue, green and red colors respectively. It can be seen that, in general, the FRE shows an increase with SZA for all the wavelengths (except for 655.9nm) with a steeper increase for absorption lines of strengths greater than 0.005nm, especially for those in the 558.6nm panel. Figure 3 shows the FRE as a function of the absorption line strengths for all SZAs (plotted as vertical data points) for three days of data obtained during the campaign. Linear fits have been obtained for all the wavelengths in each region for both low (<55°) SZA (solid line) and high (>80°) SZA (dashed line). It is apparent from this figure that the absorption line strength primarily governs the magnitude of the REC irrespective of the SZA or the wavelength. However as the linear fits show, there seems to be an increase in the FRE (between 1-15%), towards shorter wavelengths *depending* on the absorption line strength.

Discussion and Conclusions

To 'see' a clear variation of the Ring effect with absorption line strength, it is very important to *simultaneously* measure different wavelengths, as it is known that the day-to-day variations in the sky conditions (cloud coverage, aerosols, atmospheric pollution, etc.) and ground conditions (snow cover, vegetation or blue sea) have an effect on the Ring effect magnitudes [*Hunten*, 1970; *Chanin*, 1975; *Harrison*, 1976; *Conde et al.*, 1992]. In order to remove such variabilities, we have shown data from a single day (except for 630.07nm) and from one location during clear sky and no ground snow period for intercomparison among different wavelengths in figure 2. All the three days of data obtained show a similar behavior as can be seen from figure 3. Being comprehensive in nature, the results from our study also seem to offer a plausible explanation to the existing controversies in the Ring effect variation with wavelength. For example, if the absorption line strength is not taken into account, one could wrongly conclude that the FRE increases with wavelength, if one measures only two wavelengths (say 428.74 and 558.67nm) which are dissimilar in their absorption line strengths (figure 3). Also, our results indicate that in estimating the intensities of dayglow emissions that emanate in a Fraunhofer absorption region, care should be taken in accounting for the REC at this region by considering the Ring effect contribution from an absorption region that is *close* to and *similar* in strength to the Frauhofer absorption region at the emission wavelength.

We have presented an important observational finding on the dependence of the fractional Ring effect contribution on the absorption line strength. This comprehensive and high spectral resolution data set could be used in conjunction with non-linear theoretical models of Ring effect in understanding the relative contributions of various suspected mechanisms to the Ring effect, mentioned above. Plans are underway to carry out such a study in future.

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J. Baumgardner, S. Chakrabarti and D. Pallamraju, Center for Space Physics, 725 Commonwealth Avenue, Boston University, Boston, MA, 02215. USA. (e-mail:jeff@spica.bu.edu; supc@bu.edu; dpraju@bu.edu)

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