Sudden Ionospheric Disturbances

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A brief review of the recent results of the sudden ionospheric disturbances (SID) caused by solar flares has been presented; no attempt has been made to cover the whole literature on the subject. Some of the areas covered include SID phenomenology, ionization and loss processes during times of SIDs. The implications of the ion chemistry of the D-region are also discussed.

1. Introduction

It is now fairly well established that enhanced X-ray emission below 20 Å causes sudden intense ionization of the lower ionosphere, principally below 100 km. There is also evidence for some enhancement of the ionization above this level both in the E-region and the F-region, but the enhancements are considerably less, and are, therefore, more difficult to observe. This additional ionization in the ionosphere produces what are collectively called 'sudden ionospheric disturbances' (SID). These are recorded or observed by radio methods as follows:

(i) Sudden enhancement of atmospherics (SEA) at vlf and if.
(ii) Sudden decrease in the field strength of receiving signals from stations operating in the medium and short waves (either pulsed or CW), called short-wave fadeout (SWF).
(iii) Sudden decrease in the intensity of cosmic radio noise observed generally in the neighbourhood of 20 MHz, essentially similar to (ii) and called sudden cosmic noise absorption (SCNA).
(iv) Sudden increase in the signal (SES) strength received from distant if and vlf stations.
(v) Sudden changes in phase (SPA) of a received signal, first extensively measured by Bracewell and Straker on 16 MHz Rugby transmissions. SPAs have since been observed at several frequencies.
(vi) Sudden frequency deviations (SFD) during the time of an SID on long distance, highly stable frequency transmissions, believed to originate in the E- and F-regions, the exact level being determined by frequencies used, and the range of path.
(vii) Sudden changes in magnetic elements (magnetic crochet), particularly those with periodicities that are observed on magnetograms caused by modification in the arrangement of Sq currents flowing within the ionosphere.

In addition, flare effects are also observed on $f_{min}$, the minimum frequency at which reflections observable at any time on ionograms, and in the critical frequencies of the E- and F-regions, especially in $f_F$ (ref. 6, 7). Fig. 1 shows, as an example, these effects recorded during the flare event of January 30, 1968.

Recording of SIDs generally has two objectives: (i) flare patrol, and (ii) determination of the magnitudes of ionization changes in the various regions of the ionosphere and the subsequent mechanisms controlling the decay of this excess ionization.

The above effects are, however, indirect ones; these arise because of an enhancement in ionization which progressively decreases with height from a factor of 5-10 at heights around 70-80 km to about 50-100% in the E-region and about 1-20% in the F-region. Fig. 2 gives a rough picture of the different degrees of ionization enhancement at different levels. Attempts to determine these ionization changes quantitatively are relatively limited; amongst the more important efforts made are those by the Pennsylvania State University which uses a high power wave interaction technique and obtains quickrun profiles of the D-region ionization during the entire course of the flare; those by Belrose and his colleagues who use a multi-

![Figure 1](image-url) - Time curves of X-ray flux in 0.8 and 0.3 Å bands and SID effects of January 30, 1968.
frequency partial reflection technique at Ottawa; a remarkable series of profile determinations from 100 to about 300 km by the incoherent scatter equipment at Arecibo from the two large flares occurring on May 21 and 23, 1967; and two series of rocket firings by Somayajulu and Aiken into the flare occurring on January 15, 1968 and August 21, 1968. Since such works are necessarily limited, there have been several attempts to use the more conventional SID technique for profile studies. This has been done by May for the flare of October 7, 1948 with vif observations and by Deshpande and Mitra with multifrequency SCNA observations.

In any physical studies of the flare-associated ionospheric effects, it is desirable to have additionally the following information:

(i) The complete time history and the spectral distribution of the ionizing flux, along with changes in the spectral distribution.

(ii) The nature and concentration of the atmospheric constituents ionized.

(iii) The nature of the effective loss rate.

It is, however, very rare to have information on all these aspects for any one event. For (i), while entire time histories are recorded for one or more bands (e.g. 0-3 Å, 0-8 Å, 8-20 Å, 44-60 Å and 2-12 Å), it is not easy to arrive at a reliable spectral distribution out of these measurements, partly because the detector response itself is a function of the spectral temperature and partly because this temperature is not constant over the band. With regard to (ii), difficulties arise, specially in the D-region where much of the pre-flare ionization is controlled by minor constituents (such as NO for production of ionization) and the relative contributions of the different ionization sources are uncertain. For (iii), evidence exists to show that there are changes in the loss rates during a flare and that these changes may well vary from flare to flare. However, at heights above 100 km, the present evidence indicates that there is no change in the loss rate.

2. SID Phenomenology

Earlier studies of flares relating to SID phenomenology have been mainly confined to Hα flares. But with new information on flare time enhancements of XUV radiation, their time development and their changes in spectral composition below 20 Å in different bands becoming available, studies have also been initiated on the statistical characteristics of relationships between SIDs and X-ray radiation and several EUV lines (e.g. He II 304 Å, Fe XV 284 Å, Fe XVI 33 Å) which have also shown enhancements during flares.

Some important features relating to the statistical studies of SIDs, solar X-rays, radio bursts and Hα emissions are summarized below:

(i) An interesting feature of the appearance of SIDs is that if two consecutive periods are chosen so that the 10 cm flux level was lower than average in one and greater than average in the other, but there was not an abundance of Hα flares in both, then the SIDs are abundant in the latter, but nearly or entirely absent in the former. An example is shown in Fig. 3. While this example is for the period of the IGY, the same situation was found to exist during the IQSY.

(ii) A question often asked is to what extent the SIDs can be used to indicate the characteristics of other flare-associated events. The following are some of the more important results:

(a) The percentage of SIDs associated with the X-rays increases with the energy of the X-ray band. It is 60-70% for soft X-rays, but 90% for 10-50 keV X-rays.

(b) When X-ray flares occurring concurrently with Hα and radio noise bursts are considered, all types of SIDs including SCNA, SFD and magnetic crochet occur in about 80% of the cases.

(c) The capability of an X-ray flare to produce an SID effect depends on the flux level as well as on the spectral composition. It has been found that the threshold flux and the hardening factor for the 0-8 Å X-rays is (1-2) × 10^-9 erg cm^-2 sec^-1 for T = 2 × 10^6 K and 1-5 × 10^-8 respectively. Smaller fluxes can produce SIDs if the spectral hardening increases the proportion of X-ray energy below 3 Å to about 13% of the total enhancement in 0-8 Å X-ray flux. Conversely, large enhancement in 0-8 Å X-ray flux is capable of producing SIDs without much hardening.

(d) X-ray flares associated with most of the complex centimetre radio bursts (80%) and with

Fig. 3 — Plot of mean daily values of solar radio flux on 3000 MHz against days during the period August 1, 1957 to September 25, 1957 (SIDs occurring during the same period are also plotted)
impulsive and gradual rise and fall (GRF) bursts of size above 60 and 20 flux units respectively, invariably produce an SID effect.

High X-ray source temperatures are associated with class 2 and 3 flares as well as complex type of bursts. Similar findings are also reported by Teske18.

(iii) The relaxation time of SID effects with reference to soft X-ray flares is about 2-3 min. SCNA, and to some extent SWF, tend to show smaller relaxation time. The relaxation time indicates a value of \((25-40) \times 10^4 \text{ sec}^{-1}\) for \(\left(2\text{ eff}\right) N\).

(iv) Sakurai17 has discovered that when one observes SEAs on 10, 21 and 27 kHz, one can identify three separate types of events, each associated with specific types of cosmic ray events. This is shown in Fig. 4. Type A is one in which there is a sudden enhancement on all the three frequencies; type B is one in which 10 kHz is unaffected, while there is enhancement on 27 and 30 kHz, and type C is one in which there is a decrease in intensity on 10 kHz. Sakurai finds that SEAs associated with cosmic rays belong mainly to type C. Those of type sudden-C are mainly associated with B type cosmic ray particles, while the SEAs of type slow-C are accompanied by MeV cosmic ray flares of E and F types. This result shows that hard X-rays \((\lambda < 10 \text{ Å})\) were enhanced \(10^3\) times or more. Further, they are accompanied by SWFs of sudden drop-out types.

(v) When riometers are operated on more than one frequency, one can identify from a change in the frequency law as the flare progresses18, events in which the X-ray spectra have been usually

\[
\frac{L_j}{L_i} = \frac{L_j^{i}}{L_i^{i}}
\]

'hard'. Examples are given in Fig. 5. As the X-ray spectrum 'hardens', ionization is produced at increasingly lower levels where \(v^2\) begins to be comparable to \((\omega_1 + \omega_2)^2\), bringing the frequency exponent down from its pre-flare values of -2 to generally around -1.5 and in extremely rare cases to around -1.0. The information, however, is qualitative; quantitative evaluation of the X-ray spectrum of the decreasing level of peak absorption involves many assumptions.

(vi) The SID time curves in the case of flares are, in general, similar to those in X-rays or in the centimetre radio burst. Slow and impulsive radio or X-ray events produce correspondingly slow and impulsive SIDs. There are, however, differences in detail. The soft X-ray (e.g. \(\lambda 0-8 \text{ Å}, 2-12 \text{ Å}\)) enhancement begins before the SID and continues even after the end of the SID; 10-50 keV X-rays, however, correspond closely with the time of start and rate of growth of X-rays. There is some indication — this is clear in the example of the January 30, 1968 flare event (Fig. 1) — that the SID follows the time change of the spectral hardening ratio rather than the time development of X-ray flux16.

Comparison with the time histories of radio noise bursts in the centimetre range show that when an impulsive radio noise burst occurs with a clear single peak, not superimposed on GRF, the SID shows a sudden onset and a rapid rate of growth. When, however, the impulsive radio burst is superimposed on a gradual rise and fall, the SIDs correlate better with the GRF in start, in growth, as well as in later development. The impulsive burst has little connection with the SWF.

(vii) For the SFDs — the only F-region effect routinely recorded and consequently the only EUV monitoring effect — Donnelly18 has found that flare flashes of some EUV lines (e.g. He 303.8 Å, OV 629.7 Å Hlyy, 972-3 Å, C III 977 Å and Hlyy 1215-7 Å) have time dependence in close agreement with the total radiation responsible for SFDs, except during the negative decay phase, but others (e.g. Fe XV 284-1 Å, Fe XVI 335-3 Å, Si XII 499-3 Å, Mg X 625-3 Å and Ne VIII 770-4 Å, which are normally coronal lines) have a much shorter time dependence than the radiation mainly responsible for SFDs.

3. Flare-Time Ionization Profiles

Much of the information regarding the flare-time enhancement of ionization has been deduced from
## Table 1 — Summary of the Experimental Techniques to Study Flare Time D-Region Electron Density Profiles

<table>
<thead>
<tr>
<th>Method</th>
<th>Authors</th>
<th>Height range km</th>
<th>Flare events recorded</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Oct. 29, 1968</td>
<td>observations, coordinated with NRE satellite X-ray monitoring</td>
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<td></td>
<td></td>
<td></td>
<td>4. Feb. 25, 1969</td>
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<td></td>
<td>5. Feb. 27, 1969</td>
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<td>6. Mar. 12, 1969</td>
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<td>7. Mar. 17, 1969</td>
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<td>8. Mar. 18, 1969</td>
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<td>10. Mar. 20, 1969</td>
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<td></td>
<td>11. Mar. 21, 1969</td>
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<td>15. Apr. 10, 1969</td>
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<td></td>
<td>16. Apr. 21, 1969</td>
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<td></td>
<td>17. Apr. 30, 1969</td>
<td></td>
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<td></td>
<td>18. May 29, 1969</td>
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<td></td>
<td></td>
<td></td>
<td>19. Nov. 28, 1969</td>
<td></td>
</tr>
<tr>
<td>Partial reflection</td>
<td>Belrose-Certiner</td>
<td>60-85</td>
<td>Mar. 1, 1962</td>
<td>May's calculations based on Deeks profile, later modified by Bain and May</td>
</tr>
<tr>
<td></td>
<td>Delrose</td>
<td></td>
<td>Mar. 25, 1968</td>
<td></td>
</tr>
<tr>
<td>Lf/vlf phase and amplitude</td>
<td>May (1966)</td>
<td>60-85</td>
<td>Oct. 7, 1948</td>
<td>Used A2 observations on 20, 22.4 and 30 MHz at Delhi and 5.5 MHz A1 observations at Delhi</td>
</tr>
<tr>
<td>Deshpande, Ganguy and Mitra</td>
<td>60-85</td>
<td>Jan. 30, 1968</td>
<td></td>
<td>Launched during decay phase of a class 1 flare, class IB flare.</td>
</tr>
<tr>
<td>Rocket experiments</td>
<td>Somayajulu and Aikin</td>
<td>65-100</td>
<td>1. Jan. 16, 1968</td>
<td>Flights 3 min after X-ray peak. Second and third flights 12 and 24 min later</td>
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<td></td>
<td></td>
<td></td>
<td>2. Aug. 21, 1968</td>
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Fig. 6 — Profiles of electron density during pre-flare and flare times obtained by different workers

The importance of the flare of January 30, 1968, for which in addition to measurements at Delhi of SCNA on 22.4 and 30 MHz, an increase in absorption was also recorded at Calcutta at 5.5 MHz as a function of time and for the entire course of the flare event. The profile is shown along with other profiles in Fig. 6.
Another ground-based method used successfully to obtain electron density profile during flares is the wave interaction experiment conducted by Lee and Ferraro\textsuperscript{11} at the Pennsylvania State University. Fig. 7 shows the electron density profiles obtained during the flare of October 21, 1968, occurring at about 1730 UT. This was a class 2B flare with a strong X-ray enhancement (about a factor of 50 below 8 Å). The normal profile is the one obtained at about 1710 UT just before the flare began. As the flare started, the electron density $N_e$ at heights above 70 km began to increase without any appreciable change at and below 70 km (1727 UT profile). The peak effect was observed at 1739 UT, the profile at this time was quite different in shape from the normal one, suggesting a different production source during normal and disturbed times. During the decay phase the profile at 1801 UT was identical with that at 1727 UT at levels above 70 km, but was considerably different below this level. Other flares examined behaved similarly; the difference was in the degree of enhancement.

Profiles from partial reflection have been observed mainly by Belrose and coworkers\textsuperscript{13} in Canada. The two events specifically reported\textsuperscript{13} are the flare of March 1, 1962 and that of March 25, 1968.

May\textsuperscript{13} has presented some of the Cambridge vlf results during an SID event of October 7, 1948. The profile shown in Fig. 6 is for the maximum phase of the SID on October 7, 1948 (1540-1559-1635 UT) and has been deduced from the field strength measurements of the downcoming wave at 16 kHz received at steep incidence. Complete electron density profiles were derived by May\textsuperscript{13} during different times of the build-up and decay phases. Since these profiles are based on the normal electron density profile of Deeks and not the revised profile later given by Bain and May\textsuperscript{13}, they are to that extent unreliable.

Somayajulu and Aikin\textsuperscript{75} have successfully obtained electron density profiles by rocket-borne instrumentation technique from two series of flare time launchings during 1968. The first series consisted of two rocket launchings during the decay phase of a class 1 flare that occurred on January 15, 1968. The second series were flown during a class 1B flare on August 21, 1968. The first flight was during the peak of the flare profile obtained for the flare of August 21, 1968 and is shown in Fig. 6.

Comparison of the $N_a$ profiles obtained by different techniques shows that all the profiles are generally similar in shape, excepting that some have larger enhancement than others.

4. F-Region during Flares

While the ionospheric effects of solar flares in the D-region are well established, information on the flare effects in the F-region is meagre. The magnitudes of the effects are considerably less, and therefore, difficult to observe. The major evidence regarding the occurrence of F-layer effects during flare events has been obtained from:

(i) Ionosonde measurements of $f_pF_2$ at the time of the flare reported by Shapeley and Knecht\textsuperscript{1} and Minnis and Bazzard\textsuperscript{4}: This method suffers from the difficulty that for events of larger effect, precisely the ones that one wants to study, excessive attenuation causes complete fadeout in the records making any estimate of $f_pF_2$ impossible.

(ii) Observation of sudden frequency deviations during an SID on long distance, highly stable frequency transmissions by means of hf Doppler technique, first reported by Watts and Davies\textsuperscript{14}: This method is continuous, and is capable of measuring small changes in the affected layer. By operating on two frequencies it is possible to distinguish between any changes occurring in the height of reflection only or changes in the electron density below the level of reflection.

(iii) Sudden cosmic noise absorption has been used during the decay phase of the flare\textsuperscript{15} to obtain a quantitative estimation of the extent of flare effect in the F-region.

(iv) A remarkable feature of the past decade has been the development of the incoherent scatter method for the measurement of electron density, electron temperature, and other features of the upper atmosphere. An incoherent scatter radar can measure electron density by two methods. One method which is quite accurate uses the location of the plasma lines in the spectrum of the back-scattered radiation, but this is not always available. The other method is based on a knowledge of the total back-scattered power received, which is proportional to electron density. With this method, the accuracy with which electron density is measured with good incoherent scatter radar is about 5%. The height resolution is 3-6 km.

In addition to the above methods, satellite radio beacon experiment with a geostationary satellite is also used to obtain information on the F-layer during flares.

4.1 F-Region Ionization Changes

Some important results of the ionization changes in the F-region obtained by different experiments are summarized below.

From ionograms taken at Kodaikanal at 15 min intervals during the proton event of July 7, 1966, Bhattacharya and Balakrishnan\textsuperscript{53} have derived changes of electron density at six levels in the 160-220 km range. These changes are shown in Fig. 8. The normal day mean electron densities are shown by broken line curves. There was an increase in electron density at all the heights beginning at nearly the same time as the optical flare. There were two maxima; the authors attributed the first (occurring at about 0630 IST) to the solar XUV...
radiation, and the second (occurring immediately after 0070 UT) to collisional ionization by high energy particles from the sun. We also note that there is a progressive delay in the time of maximum ionization as we go to higher levels.

Profile studies have also been made by Donnelly from observations of SFDs. An example is shown in Fig. 9. This profile was derived for the proton flare of August 28, 1966, from oblique incidence (Illinois-Boulder) SFD observations on 89 and 111 MHz and vertical incidence observations on 5054, 400, 3300 and 2108 MHz. This was an unusually large SFD event.

The incoherent scatter results, mainly from Arecibo, are obtained from simultaneous observations of the following: Total power in the ion component of the back-scattered spectrum as a function of height and time at 480 MHz; plasma-line echoes observed in 0-5 MHz steps from 3.5 to 9.5 MHz below the transmitted frequencies reflecting in the F-region. The results indicate:

(a) Fairly large enhancements in the E-region, decreasing with height in the region, but with discernible enhancements up to 300 km.
(b) Delayed time of onset of the enhanced ionization at levels above the E-layer, becoming most pronounced at F-layer heights.
(c) A negative fluctuation at F-region heights over the flare-affected region.

For the May 1967 events, probed by the Arecibo incoherent scatter equipments, Garriott et al. from the observations of the vhf telemetry signals received at Stanford, San Diego, Flagstaff and Ely from the geostationary satellite ATS 1 at 137-35 MHz, have reported that an increase in electron content of about $2 \times 10^{16}$ elm$^{-2}$ (about 5% of the total ionospheric content) was observed. The smaller value is expected because of the contributions from heights above 200 km where ionization enhancement is only a few per cent.

### TABLE 2 - AVERAGE ENERGY (IN ERO/cm²/SEC) OF IONIZING RADIATION

<table>
<thead>
<tr>
<th>Band</th>
<th>Control period</th>
<th>Flare period</th>
</tr>
</thead>
<tbody>
<tr>
<td>44-100 Å</td>
<td>0.25</td>
<td>1.10</td>
</tr>
<tr>
<td>200-900 Å</td>
<td>0.09</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Fig. 9 — Electron density profiles during the flare deduced from SFD data
insensitive to smooth enhancements of radiation with rise times greater than 5 min, because then the loss process nearly balances the production rates. Donnelly finds that high energy X-rays ($\lambda < 0.6 \, \text{Å}$) and Ly$\alpha$ enhancements do not contribute significantly to SFDs, 10-100 Å X-ray bursts are of minor importance to SFDs, 10-100 Å X-ray bursts do contribute significantly to SFDs (a point in agreement with the observations of Bhattacharya and Balakrishnan), and that flashes of radiation of wavelengths longer than 100 Å are required to explain most SFDs. In a more recent work, Donnelly compares SFDs with OSO-3 EUV measurements from AFCRL and Explorer-35 X-ray measurements from NRL to further resolve the wavelength dependence of the radiation responsible for SFDs. The comparison was three-fold—a comparison of time dependence, intensity and transmission frequency dependence. It was observed that the EUV enhancements in He II 303.8 Å, OV 689.7 Å, H Ly 972.5 Å, C III 977.0 Å, and HL O 1215.7 Å had the same time dependence as the net X-ray production rate at that time can provide vital information on the upper limit of nitric oxide concentration.

A quantity of much controversy has been the magnitude of the non-X-ray production rate in the D-region. The controversy rests principally on the concentration of nitric oxide for which there was for several years an order of magnitude difference between the rocket deduced values and ionospheric estimates. An accurate measurement of the changes in electron density during an X-ray production rate at that time can provide vital information on the upper limit of nitric oxide concentration.

This has recently been attempted by Rowe et al. for the flare of October 21, 1968, shown in Fig. 7. The integrated X-ray flux in the bands 0-3 Å, 0-8 Å and 8-20 Å was measured during the entire history of the flare by the photometers aboard the SOLRAD 9 satellite. Spectra were calculated for different times of the flare and X-ray production rates were computed at these times. A comparison of the time histories of $N_e$ and the X-ray production rate was made at different D-region levels. It was found that $q_1$, the non-X-ray production term, depends on the pre-flare values of $a_o$, $a_h$ and $\lambda_o$. The Penn State approach was to assume values for $q_1$ for the effective ion-ion recombination coefficient $\xi_i$ and for normal noon value of $\lambda(=\lambda_o)$. The equilibrium equation of the rocket deduced values was then solved for $a_o$. The differential equation was then integrated numerically using the above values, and using time histories of $N_e$ and $q_1$. The conclusion was that $q_1 < 10^{-7} \, \text{cm}^3/\text{sec}$ and $\lambda_o < 8$; $q_1$ is probably about 3 or 4 cm$^3/\text{sec}$ if $\lambda_o$ is about 5. If all of the $q_1$, 80 km is due to $L_2$ ionizing NO, then $n(\text{NO}) \approx 3 \times 10^7$ cm$^{-3}$ at 80 km.

Similar analysis was made for the flare of March 27, 1969 (1630-1700 UT), giving for an upper limit of 6 cm$^3/\text{sec}$-1. This would correspond to an NO concentration of $2.4 \times 10^7$ cm$^{-3}$, whereas the constant loss rate analysis gives $n(\text{NO}) \approx 3 \times 10^9$ cm$^{-3}$. 

5. Aeronomy Studies during Flares

5.1 Information on Nitric Oxide from Simultaneous Measurements of Electron Density and Solar X-rays during Flares

The differential equation of the rocket deduced values was then solved for $a_o$. The differential equation was then integrated numerically using the above values, and using time histories of $N_e$ and $q_1$. The conclusion was that $q_1 < 10^{-7} \, \text{cm}^3/\text{sec}$ and $\lambda_o < 8$; $q_1$ is probably about 3 or 4 cm$^3/\text{sec}$ if $\lambda_o$ is about 5. If all of the $q_1$, 80 km is due to $L_2$ ionizing NO, then $n(\text{NO}) \approx 3 \times 10^7$ cm$^{-3}$ at 80 km.

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5.2 Loss Rates during Flares in D-Region

Conclusive evidence has been obtained to show that the effective recombination coefficient in the D-region decreases rapidly and by a large amount during a flare, reaching its minimum value shortly after the peak electron density is reached. Much of the evidence has come only recently. Rowe et al. found that for the flare of October 21, 1968, for all reasonable values of NO, the observed electron densities would require a decrease in the effective recombination coefficient, by as much as a factor of 5 at 80 km. A similar analysis made by Deshpande et al. for the major flare of January 30, 1968 gave similar results. Further evidence came from the work of Deshpande and Mitra who derived the changes for a large number of flare events and from the work by Mitra and Rowe from experimentally observed values of $Q/N_2^2$ at 80 km. In Fig. 11 these different results, representing different flare conditions, are compared with the recombination coefficient profile given by Reid [the profile has been modified by using Mitra’s NO distribution and Huffman’s estimate of $q(O_2/N)]$. In all cases the loss rate profiles are lower than Reid’s. If Reid’s profile is considered to represent the normal equilibrium situation, we have evidence of a decrease in $\psi$ during flares at all D-region heights. It may be noted that there is a systematic decrease in the loss rate profile with increasing flare intensity. The $\psi$-profiles constructed by Mitra and Rowe to represent weak, moderate and strong flare conditions are given by the dashed curves in Fig. 11.

5.3 F-Region Loss Rates during Flares

Calculations of loss rates in the F-region during flare events are scarce. Donnelly has determined $\sigma_{\text{eff}}$ using OSO-3 measurements of $H_2$ II 303.8 Å, OV 630.1 Å, Ly $\alpha$ 1216 Å and C II 1335 Å along with Doppler frequency changes in SFDs. He obtains $\sigma_{\text{eff}} = 2 \times 10^{-7}$ cm$^2$ at 100 km and $1 \times 10^{-7}$ cm$^2$ at 160 km. The first is entirely consistent with laboratory data. No work exists to show that there has been any change in the loss rate or in the ion chemistry of the F-region during a flare. Ion composition measurements would be valuable in this respect.

6. Changes in D-Region Ion Chemistry during Solar Flares

Mitra and Rowe have introduced a new ion chemical scheme consisting of six ions (four positive and two negative) to explain the decrease in $\psi$ in the D-region during a solar flare. The scheme is given in Fig. 12. At normal times the precursor ion for clustering is most likely NO$^+$. During the flare we suddenly have a large supply of O$_2^+$ ions produced both through direct photo-ionization of O$_2$ and through charge transfer from N$_2^+$. Clustering through O$_2^+$ is now possible. At this stage the back reaction

$$O_2^+ + O \rightarrow O_2^+ + O_2$$

becomes operative, virtually blocking the clustering process and returning the ions to the simple molecular stages, namely O$_2^+$ and NO$. There is thus a decrease in the percentage of hydrates as $q$ increases and a corresponding increase in the percentage of simple ions. Since hydrates have a dissociative recombination coefficient about an order of magnitude larger than NO$^+$ and O$_2^+$, there is a rapid decrease of the effective recombination coefficient. As one might expect, larger concentration of O makes the simple ions increase faster as $q$ is increased; the opposite effect occurs with H$_2$O. For large values of $q$, the positive ion chemistry reduces to the situation of simple molecular ion chemistry and $\sigma_{\text{eff}}$ is that of molecular ions only, i.e. about $10^{-6}$ cm$^3$/sec. The levelling off occurs at $q_s = 500$ cm$^3$/sec at 80 km.

Fig. 12 — A new ion chemical scheme

References

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