The Thermospheric and Ionospheric Response to Solar Flares

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Outline

Introduction

Thermospheric Response to Real Flares

Thermospheric Response to Ideal Flares

Ionospheric Response to Flares

Conclusions
Introduction

• Solar flares are impulsive increases in the extreme ultraviolet and x-ray irradiance from the sun
  – Rise time of several minutes
  – Decay time of minutes to hours.

• They mostly originate from active regions
  – Can be associated with reconnection events on the sun. These sometimes release coronal mass ejections.

• Flares come in different classes: C, M, X
  – Classification on maximum intensity in X-ray wavelengths
    • Does not quantify total energy going into the system.
    • Does not quantify which wavelengths are strongest.
      – Higher energies deposit energy lower in atmosphere, while lower energies can deposit more energy higher in the atmosphere.
  – Each is a factor of 10 larger than the last.
Problem

• Flares can not be observed from the ground
  – Well, super large flares can have visible effects, but most don’t
• F10.7 does not capture flares, since it is ground-based daily measurements
  – Flares can effect the F10.7 measurements, and can lead to overestimation of the solar flux for the day
• Need to have measurements from space
  – GOES – takes X-ray measurements in a few channels every minute
  – TIMED SEE – took measurements across the spectrum every orbit (90+ minutes)
  – SDO – takes measurements of the solar spectrum every minute
• FISM – Flare Irradiance Spectral Model
  – Takes any measurements of the solar spectrum and attempts to tie them together to create a complete spectra every minute.
  – Before SDO was launched, FISM used GOES X-rays for temporal evolution, and SEE data for spectral characteristics.
  – Uses F10.7 to make sure the spectra are consistent from day-to-day.
Questions

• How does the thermosphere respond to solar flares?
  – General characteristics of the response?
  – How does the intensity of the flare control the response?
  – How do flare characteristics (peak energy, total energy, rise time, decay time) control the response?

• How does the ionosphere respond to flares?
  – How do the background conditions determine the response?
Method

• Use measurements from TIMED SEE and GOES to create 1-min resolution spectra for different flares
• Use the Global Ionosphere Thermosphere Model (GITM) to simulate response
  – Compare to different data sets to verify response is consistent
  – Run simulations with and without the flare, then subtract to explore response due to flare
• Make up different flares and run idealized simulations to explore how characteristics of flare alter the thermospheric response
• Move flares to different times to explore how background conditions alter ionospheric response
Global Ionosphere Thermosphere Model

GITM solves for:
- 9 Neutral & 5 Ion Species
- Neutral winds
- Ion and Electron Velocities
- Neutral, Ion and Electron Temperatures

GITM Features:
- Solves in Altitude coordinates
- Can have non-hydrostatic solution
  - Coriolis
  - Vertical Ion Drag
  - Non-constant Gravity
  - Massive heating in auroral zone
- Runs in 1D and 3D
- Vertical winds for each major species with friction coefficients
- Non-steady state explicit chemistry
- Flexible grid resolution - fully parallel
- Variety of high-latitude and Solar EUV drivers
- Fly satellites through model

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Two Example Flares

- October 28, 2003 and November 6, 2004 Flares
- October flare > 10x November flare
- Used GOES 1-min X-ray measurements to interpolate TIMED SEE data
- Determining peak intensity of non-X-ray wavelengths is hard
October 28, 2003  Flare Response

Dayside = SZA < 30°
Dashed is maximum perturbation within SZA < 30°
Solid is geometric mean perturbation for SZA < 30°
~13%-15% perturbation in mass density at 400 km

Nightside = SZA > 150°
Dashed is maximum perturbation
Solid is mean for SZA > 150°
~10%-13% perturbation in mass density at 400 km

~3 hour delay between day and night reaction
Indicates large-scale gravity wave
(Rotation of Earth would take 12 hrs)
November 6, 2004 Flare

Dayside = SZA < 30°
Dashed is maximum perturbation
Solid is geometric mean perturbation over SZA < 30°
~3%-4% perturbation in mass density at 400 km

Nightside = SZA > 150°
Dashed is maximum perturbation
Solid is geometric mean perturbation over SZA > 150°
~2%-3% perturbation in mass density at 400 km

~3-4 hour delay between day and night reaction
Large-Scale Gravity Wave

- Percentage difference in mass density versus solar zenith angle
  - Averaged in 7.5° solar zenith bins from 0° to 180°
- Each color represents a different time separated by ~15 minutes from 11:15 to 13:15
  - Flare initiated just before 11:00 UT

1. Density increase with time
2. Density decrease with time (indicates heating is above this location)
Large-Scale Gravity Wave

- Percentage difference in mass density versus solar zenith angle
- Each color represents a different time
- Large scale gravity wave visible.

1. Density increase with time
2. Density increase propagating towards night side
Large-Scale Gravity Wave

- Percentage difference in mass density versus solar zenith angle
- Each color represents a different time
- Large scale gravity wave visible
- No propagation evident below at 140 km and below.

1. Density increase with time
2. Density increase propagating towards night side
3. No significant propagation seen here
Large-Scale Gravity Wave

- Percentage difference in mass density versus solar zenith angle
- Each color represents a different time
- Large scale gravity wave visible above about about 140 km altitude.

1. Density increase with time
2. Density increase propagating towards night side
3. No significant propagation observed here
4. Some evidence of propagation observed here
Night-to-Day Wave Propagation

- Once wave reaches the nightside and density increase fully develops, the density starts to decrease.
- Wave passes through midnight region and perturbation propagates towards the dayside.
- Secondary intensification is observed on dayside.
CHAMP vs GITM for October Flare

CHAMP Dayside
- Primary peaks are consistent
- Secondary peaks are harder to ID

GITM Dayside

Point measurements at -2° latitude for both CHAMP (solid) and GITM (open)

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Summary

• Thermospheric response is definitely dependent on the flare size
• Large-scale gravity wave launched as flare goes off
  – Travels from dayside to nightside
• Peak on nightside is evident
  – About 3-4 hours later
  – Similar in magnitude as the dayside perturbation, just a bit smaller
  – Traveling with day-to-night winds
• Evidence of secondary dayside peak as wave propagates back towards noon
  – Fighting against day-to-night winds
  – Significantly weaker
Ideal Flares

• In order to determine how the flare characteristics drive different responses in the thermosphere, we conducted a large number of simulations, systematically altering characteristics of the flare
  – All flare spectra are based on the Oct. 28, 2003 flare
  – When flare characteristics are changed, they are changed for all wavelengths in exactly the same way
  – Altered decay time of flare to allow more energy to enter the system without changing peak energy or rise time
  – Altered peak intensity and decay time to keep total energy of the flare the same
  – Altered the rise time and decay time to keep total energy the same, but allow different rise times.
Dependence on Total Energy

• Each flare has the same peak intensity
• Rise times are identical also
• Decay times are altered to allow more energy to enter the thermosphere
• Thermospheric Response of mass density at 400 km is clearly dependent on total energy, and not peak energy!

As total energy increased, global average density perturbation increased

As total energy increased, global maximum density perturbation increased
- Can see dayside peak (first) and nightside peak (second)
Dependence on Decay Time

- Each flare has the same total energy
- Peak times are identical, but peak intensities are altered
- Decay times are increased to allow lower peak intensity, but same amount of total energy
- Mean thermospheric response is only slightly dependent on peak intensity!
- Maximum thermospheric response is strongly dependent on the peak and less dependent on the total energy
- Timing of when the maxima occur (both nightside and dayside) strongly dependent on decay time

As decay time increased, global average density perturbation slightly decreased, but not by much

As peak energy increased, global maximum density perturbation increased

Timing of peaks is dependent on decay time!
Dependence on Rise Time

- Each flare has the same total energy
- Rise times are altered
- Decay times are changed to allow same amount of total energy
- Mean thermospheric mass density response is only slightly dependent on rise time!
- Maximum thermospheric mass density response is not dependent on rise time
- Timing of when the maxima occur not dependent on rise time
Role of Nitric Oxide

- Simulations of same total energy but different peak energies and decay rates
- More Nitric Oxide is created for larger peaked flares
- Increases cooling early in the flare
- Thermospheric response is a balance between heating and cooling, and NO density plays a role in this!

NO cooling is strongly dependent on peak energy!
This causes a cooling of the thermosphere in the beginning of the flare
Summary

• Mean and maximum thermospheric mass density response is strongly dependent on the total amount of energy entering the system

• Mean thermospheric mass density response is not very dependent on the peak intensity of the flare

• Maximum thermospheric mass density response is strongly dependent on the peak intensity of the flare
  – Timing of when the peak of the mass density response happens is strongly dependent on decay time of flare
  – Longer decay time delays the time of the peak mass density response.

• Rise time of the flare is not very important
  – Mean mass density response is weakly dependent on the rise time, due to creation of NO density, which cools the thermosphere

• Nitric Oxide drives cooling in the thermosphere, and is created during solar flares, so energy balance must be fully considered
Ionospheric Response to Flares

- Explore the October 28th, 2003 solar flare
- Look at total electron content
- Use the same simulations as were shown in the first part of the talk
TEC Response as a Function of Time

- Global max TEC has several peaks (day and night), and is very large!
- Global mean TEC peaks just after flare and decays slowly
- Global min TEC is large and peaks well after flare!
- Global maximum propagates from day to night
- Then through midnight towards dawn

Oct 28 to 29, 2003 UT Hours
TEC every hour after the flare

Ion drifts superposed

Increase on dayside just after the flare

Structures on nightside develop hours after the flare

These are due to neutral winds driving ion drifts up and down field-lines
Summary

• Mean global Total Electron Content reacts similarly to the mass density – peaks just after the flare peaks and decays slowly.

• Structures develop in TEC due to neutral winds pushing ions up and down field lines.

• Not shown:
  – The nightside structure is strongly dependent on the background conditions, due to the neutral winds and interaction with magnetic field.
  – Polar region response is strongly dependent on season.
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• Total energy of solar flare is the primary driver of the global thermospheric response
  – Rise time and time of the peak intensity matters a bit because a faster rise time will create more Nitric Oxide early in the flare, which can start to cool the atmosphere
  – But, overall this effect is pretty minor

• Peak intensity of the solar flare drives the maximum perturbation in the thermosphere

• Global ionospheric TEC mean response to a flare shows a rapid increase, then very slow decrease
  – There is a rapid increase of the TEC on the dayside, then a propagation towards the nightside.

• Significant structure in the ionosphere can develop during and after a flare due to the neutral winds and their interaction with the magnetic field
Questions?

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