D. J. Knipp *et al., The May 1967 great storm and radio disruption event: Extreme space weather and extraordinary responses*, Space Weather, 14, 614–633

The article can be accessed at
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016SW001423

You can also download the Cornell notes template for this paper (which includes the same questions) as a Word Document or PDF. Teachers, feel free to download this and forward it on to your students.

This week's article focusses on the fascinating subject of *space weather*. This is something we have probably not even considered before, but is a series of dramatic events within the sun that can have cataclysmic effects on earth. The paper details one such solar storm, explaining the events of the solar storm itself, exploring how this storm affected the earth and the consequences of this storm to humankind due to its effect on our communication channels. As always, pay attention to the questions as we go along as there are some sections we might skip.

We're going to start with a skim read. Don't worry if it doesn't make complete sense, or if you skim some sections quicker than others as you're feeling uncomfortable with them, that's fine. There are a LOT of acronyms and initialisms in this paper which make understanding it more complicated for novices, but we'll create a dictionary of them in a second. But for the moment, give the article an initial skim-read now to get a feel for what we're going to study.

Rather than doing our **SKIM-READ QUESTIONS** this week, we're going to concentrate on **KEY DEFINITIONS** that'll be important to understand for a thorough reading of this article. Below is a list of key terms that you're probably less familiar with from the article. Write a short but clear definition for each and submit these along with you **SUMMARY QUESTIONS** at the end of the article.

Coronal Mass Ejection	
Geomagnetically induced currents	
Geomagnetic storm	
Ionospheric storm	
Magnetosphere	
Plasma eruptions	
Solar cycle	
Solar flare	
Solar radio burst	
Sunspot	

Below is an alphabetised list of the acronyms and initialisms in this paper to refer to if you forget what they mean (I used this all the time – I don't expect you to remember these). NOTE ON PEDANTRY: an acronym is a series of initials from a phrase that can be pronounced as a word e.g. LASER and NASA, an initialism is a similar abbreviation, but isn't pronounced as its own word e.g. FBI and DVD.

4WW	Fourth Weather Wing
AF	Air Force
AFB	Air Force Base
AFGWC	Air Force Global Weather Central
AR	Active Region
AWS	Air Weather Service
BMEWS	Ballistic Missile Early Warning System
CME	Coronal Mass Ejection
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
ESSA	Environmental Science Services Administration
EUV	Extreme Ultraviolet
GIC	Geomagnetically Induced Currents
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
HF	High frequency
ICBM	Intercontinental Ballistic Missiles
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Air Defense
PCA	Polar Cap Absorption
RFI	Radio Frequency Interference
SAC	Strategic Air Command
SDFC	Space Disturbances Forecast Center
SDL	Space Disturbances Laboratory
SEON	Solar Electro-Optical Network
SESS	Space Environment Support System
SID	Sudden Ionospheric Disturbance
SOFNET	Solar Observing and Forecasting Network
SPE	Solar Proton Event
SRB	Solar Radio Bursts
SSC	Sudden Storm Commencements
SWPC	Space Weather Prediction Center
USAF	United States Air Force

ABSTRACT

Analyse the phrase “intense fluxes of ionizing solar X-rays” word-by-word to understand its meaning.	Intense: extreme strength Flux: outward flow Ionising: has the ability to ionise (in this case remove electrons) from an atom Solar: pertaining to the sun X-rays: a high energy part of the electromagnetic spectrum In total: a significant amount of high energy electromagnetic radiation was emitted from the sun with the ability to ionise material that it interacted with.
What positive outcomes were there from the “Great Storm” of May 1967?	An increased focus on understanding and predicting space weather. The American Department of Defence began to support scientists in forecasting space weather.
Summarise the abstract in two sentences.	

1.1 Intersection of Nature and Politics

What happens during a ‘rise’ in a solar cycle?	There is an increase in solar activity – an increased number of sunspots and an increased number of solar flares.
What is the hydrogen-alpha line?	A spectral line corresponding to one of the transitions for an electron within Hydrogen. Specifically it’s from the third lowest to the second lowest energy level.
Why is the hydrogen-alpha line important to astronomers?	Given that stars (including our sun) contain a significant amount of hydrogen (their fuel for nuclear fusion), the hydrogen-alpha line can be used to look at features in the sun’s atmosphere.
How do astronomers obtain an image of the sun in the hydrogen-alpha region of the spectrum?	Using a filter centred on the wavelength of light (656.28nm) that corresponds to the hydrogen-alpha transition.
What is the interplanetary medium? What does it contain?	The interplanetary medium is the material within the region in between planets. Whilst we tend to think of this region as a vacuum, it actually contains interplanetary dust, cosmic rays and hot plasma from the sun as well as electromagnetic radiation and magnetic fields.
Considering the quote at the bottom of page 1, why is it crucial for space weather information to be widely shared?	Because the impact of space weather has significant effects on communication. These communication channels

1.2 Cold War and Military Background

Describe how radio communication works. This will be one of our **SUMMARY QUESTIONS** but try to answer this now. You may find this video helpful	
What is the doctrine of 'mutually assured destruction'?	When two (or more) nations are armed with nuclear weapons, and the knowledge that they both have them, a state of equilibrium is reached. The strategy is a form of Nash equilibrium in which, once armed, neither side has any incentive to initiate a conflict or to disarm as their destruction is guaranteed either way.
Why would radio disruptions significantly affect Strategic Air Command (SAC) communications?	Because SAC communications were conducted extensively in the radio range
What does the frequency of a wave tell us?	How many cycles occur per second. A 1Hz wave has 1 complete cycle per second. A 1MHz wave has 1million cycles per second.
What frequency band do Strategic Air Command (SAC) communications use? What part of the electromagnetic spectrum is this in?	6-30MHz. The radiowave part of the EM spectrum
What frequency does the Ballistic Missile Early Warning System (BMEWS) use? What part of the electromagnetic spectrum is this in?	440MHz. This is at the top of the radio or bottom of the microwave part of the EM spectrum (microwaves start around 330MHz).
"NORAD and SAC operations were inextricably linked as they shared early warning data; however, decisions related to the data could result in independent actions" What does this tell you about how people handle data?	That the interpretation in your particular context may lead you to take very different actions.
What motivated the setup of space weather observations leading up to 1967?	The end of World War II and the need to ensure strong radio communication channels.
Why did NORAD, and specifically its radars, need the support of solar weather understanding?	Because the radars would experience solar and auroral interference.

1.3 A Brief Guide to Solar and Geomagnetic Disturbances With Emphasis on Radio Effects

Look carefully at figure 2, what are the two events that occur within the sun that cause this 'myriad of space weather radio effects'?	Solar flares and coronal mass ejection
In figure 2, which space weather disturbance takes the longest to affect earth?	Magneto/Ionospheric storms
In figure 2, which space weather disturbance lasts for the shortest amount of	X-ray emission

time (be careful and remember it's a log scale).	
In the figure caption there is an example description of one of the events – it begins 'as an example, energetic protons…' Read this and understand how they've written this from the information in the figure. Write one of your own for a different solar weather disturbance in the figure.	
What are Active Regions (ARs)?	Regions with multiple solar emissions in or above sunspots. Here the magnetic field is very strong and has a twisted shape.
" When energy density in AR magnetic fields reaches a tipping point, the fields reconfigure, producing bursts of electromagnetic energy (flares) across a broad spectrum of wavelengths: X-ray, extreme ultraviolet (EUV), UV, visible, and radio emissions. Some very strong flares produce gamma ray and intense white-light emissions". Using the video at this link, explain briefly the process of magnetic reconnection that is being discussed here.	
At what speed do the electromagnetic waves emitted by the sun travel?	$3\times10^{8}ms^{-1}$
What are the two ways that radio communications can be affected by the influx of electromagnetic radiation? (HINT: These come under the category of sudden ionospheric disturbances).	They can be directly affected by interference from the radio emissions of the sun. They can be indirectly affected as the x-ray and extreme ultraviolet emissions change the ionisation energies of elements in the earth's upper atmosphere, limiting the propagation of radio waves and actually causing absorption of the higher frequencies.
What is plasma?	Ionised gas – it contains the ions that have had some of their electrons removed and the free electrons.
What are supersonic speeds?	Speeds higher than the speed of sound in air.
Why can't the coronal mass ejection (CME) travel at the speed of light?	Because the CME contains particles with mass and these cannot reach the speed of light.
How do coronal mass ejections (CMEs) lead to an increased amount of radio transmission?	As they travel through the outer atmosphere of the sun, the CME interacts with the plasma it encounters, causing the emission of further radio waves. Imagine this from the perspective of the particles within the plasma: the ion cores can still be excited (given energy) so that electrons move up energy levels and then drop down, emitting photons.

If a CME takes 2-4days to reach earth, on average, then lets assume it takes 3days. At what speed has the CME travelled?	Distance from sun to earth is ~150million km (1.5×10^{11}m). 3days=259200s. This is a speed of ~$5.8\times10^{5}ms^{-1}$
What are solar energetic particle events?	Highly energetic protons and electrons ejected from the sun at the site of a flare or at the front of a coronal mass ejection.
Why are solar energetic particle events normally called solar proton events?	Since protons have a much larger mass than electrons, they carry more momentum?
Why can solar energetic particle events travel faster than a CME?	Since, on average, the particles (protons and electrons) in solar energetic particle events are lighter than the particles (ion cores and electrons) in CMEs, they can travel faster.
How can radio communication be affected by solar energetic particle (or solar proton) events?	Long lasting solar energetic particle events are called radiation storms. In the polar regions of the earth, these radiation storms can lead to changes in the gasses in the atmosphere that give rise to the absorption of high frequency radio signals (Polar Cap Absorption events).
Why do the equatorial latitudes experience these radio interferences “primarily from dusk to dawn”.	Because this is when those regions are facing the sun and are the target for the radiation that is travelling towards the earth.

Now, section 2 (May 1967 Solar-Geophysical Background and Details— What We Know Now) is a bit on the heavy side. I’d encourage you to read it to see if what you’ve researched so far makes this section more understandable, but we’re not going to have questions on this section as it’s quite dense. The section gives all of the detail about the storm of May 1967 – the timings of events and the types of solar events that happened and whereabouts on the sun. We’re going to dip back into questions at the end, section 2.4

2.4 How Severe Were the May 1967 Storms?

What is a solar flux unit?	A unit of power per metre squared to quantify the average flux per frequency of radiation from the sun received on earth. 1solar flux unit = 1 $Wm^{-2}Hz^{-1}$
Why is it difficult to list which solar storms are ‘worst’?	Because each different event is measured differently, and different parts of the earth experience it differently. Quantifying the disruption to radio signals is essentially impossible
If this storm is not top of all of the quantifiable lists, and would actually seem to be a not uncommonly large storm by many metrics, what made it so bad?	The timing of the storm on earth in relation to the political tensions that were occurring meant it could have been catastrophic for humans.

3. Discussion: Storm Impacts and Legacies

3.1. May 1967 Storm Impacts: Radio Frequency Interference and Space Weather Support

What is military jamming?	Intentionally sending out radio signals to interfere with RADAR and other communication devices by overwhelming them with false signals.
Why would a solar radio burst be misinterpreted as jamming?	Because the measured signals would look very similar – intense bursts of radio. And if you were in a political situation where you might expect 'the enemy' to be using such measures, then that's what you'd immediately conclude.
What role did NORAD play in calming the tensions?	Through their analysis and the communication of it, they concluded that the BMEWS (Ballistic Missile Early Warning System) and similar technologies should expect to see large radio bursts, and that they shouldn't necessarily be interpreted as military jamming.
If military bombers has been launched, why might it have been difficult to recall them had the NORAD message come through later?	Due to the radio interference effects of the solar radio bursts, the communication channels between the command station and the bombers would be expected to be disrupted. The bombers are trained to carry out their orders unless they hear otherwise, so everything hinged on the radio communication.

3.2. Legacy: U.S. Air Force Space Environment Support System

What data can optical instruments give us about solar weather?	Sunspots, flares, filaments, and magnetic field configuration.
What data can radio instruments give us about solar weather?	Radio sites monitor the radio interference and emissions at discrete frequencies. Additionally, radio spectrographs sweep their observations to search for signals of moving transients in the solar atmosphere.
Why is it valuable to have staff trained across several areas e.g. Air Weather Service staff being trained in space weather.	To allow people to understand all possibly causes of signals in their data/observations. To give additional/different perspectives on topics.

THE AURORA

One consequence of space weather on earth that is less catastrophic is the aurora borealis or northern lights. One of our summary questions this week will be to explain this phenomenon in relation to space weather. Here are a few links to get you started:

https://www.aurorahunter.com/what-are-the-northern-lights.html

https://earthsky.org/earth/what-causes-the-aurora-borealis-or-northern-lights

SUMMARY QUESTIONS (submit these, along with your KEY DEFINITIONS and answers to thomas.millichamp@warwick.ac.uk)

Describe how radio communication works.

In the case of space weather, why are science and politics often intertwined?

How might the modern world be affected by significant solar weather effects?

Why does the aurora borealis (northern lights) occur? Your answer should include some of the specifics of what elements of space weather cause it and how these space weather events occur. Also, I want you to keep your explanations SIMPLE. Imagine this being read by the general population, but you wanted to help them understand the real science that is going on. I don't want your answer to be EASY, that's not the goal, I want your writing to be SIMPLE but DETAILED. This is very difficult, but a good thing to practice. This should take more than one draft.

FURTHER READING

NASA have a lot of pages dedicated to space weather:
https://www.nasa.gov/mission_pages/rbsp/science/rbsp-spaceweather.html

This WIRED article looks at some of the extreme effects of space weather

https://www.wired.com/2013/03/rethinking-space-weather/

This BBC World Service piece discusses space weather and its effects

https://www.bbc.co.uk/sounds/play/w3csy1ql