
2010

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Forrester, Gary (2010). Solar Observations During a Solar Minimum Using a Small Radio Telescope. *Undergraduate Review*, 6, 77-82.

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Solar Observations During a Solar Minimum Using a Small Radio Telescope

GARY FORRESTER



Gary is a recent graduate of Bridgewater State College with majors in Physics and

Mathematics. His research was funded with a 2009 Adrian Tinsley Program summer grant under the mentorship of Dr. Martina Arndt of the Physics Department. This work was accepted for presentation at the 2010 National Conference for Undergraduate Research. Gary plans to study Astrophysics in graduate school.

The Sun is currently in a quiescent phase called solar minimum. We used Bridgewater State College's (B.S.C.'s) Small Radio Telescope (SRT) to observe solar radio emission during this quiet phase and correlated our data to solar X-ray data readily available through the National Oceanic and Atmospheric Administration (NOAA). Previous observations made during a period of high solar activity (solar maximum) using one of M.I.T.'s SRTs showed that some solar radio and X-ray events were correlated, while others were not. We made observations during solar minimum and found one event where there was a correlation between radio and X-ray emission.

Introduction

Radio astronomy is a very important aspect of astronomical observations. It accounts for 65% of all of observations made of our universe[6]. Many important discoveries have come from radio astronomy such as the cosmic microwave background, dark matter, quasars, pulsars, and detection of black holes. Because of their long wavelengths, radio waves are unimpeded by stellar dust and allow us to see the most distant objects and even peer through the dust of galaxies to see their inner structure.

Studies of radio emission from the Sun are particularly important because they give us some insight into the structure of solar flares. Solar flares can affect our infrastructure here on Earth. They have been associated with large-scale blackouts as well as satellite and GPS malfunctions. Solar activity has also been connected with our climate and could have a significant impact on our atmosphere.

The Sun is the nearest star to Earth. Information gathered about processes on the Sun helps us understand more remote, and often more exotic, stars as well. The Sun emits light in every wavelength in the electromagnetic spectrum – from gamma rays to radio waves. For our work, we focused on radio (lower energy) and X-ray (higher energy) emission from solar flares, and the mechanisms responsible for it.

The Sun cycles between high (solar maximum) and low (solar minimum) activity phases every 5 to 6 years; we are currently in an extended solar minimum. The last solar maximum occurred between 2000 and 2003, and solar physicists expect the next solar maximum to take place in 2012. Since

the Sun is currently in a minimum phase we expect to see fewer flares, and while that leads to less radio and X-ray emission, it does reduce ambiguity about the location of the source of any emission we detect.

In our project, we observed radio flux from the Sun and compared it to NOAA X-ray flux data. This experiment was done in 2002, during solar maximum, at MIT's Haystack Observatory and they found a strong correlation between X-ray and radio emission from several events. Our goal was to see if we could observe any correlated events during a 10 week period during solar minimum.

Solar Flares

A Solar flare is a sudden, swift, and intense variation in brightness on the Sun from a sunspot [7] and results when energy from the Sun's magnetic field builds up and is suddenly released. These events have energies that are several hundred times the energy involved in a hydrogen bomb explosion[1]. Radiation from solar flares is emitted in every wavelength in the electromagnetic spectrum, from low energies to high.

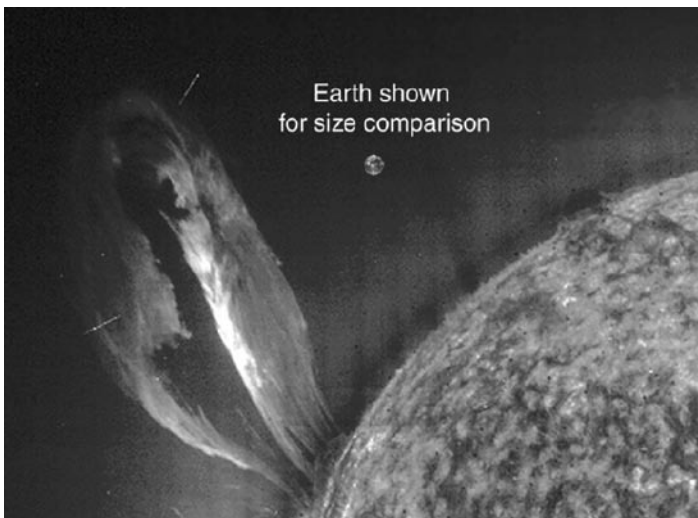


Figure 1: A Solar Flare Compared With the Size of the Earth (Courtesy of TeachEngineering.org)

Solar flares are broken up into several phases: the precursor phase, when the magnetic field energy is released; the impulsive phase, with the most intense emission, when electrons, protons and ions are accelerated to near the speed of light; and the decay phase, where radiation emission gradually decays to normal levels. All of these phases can last from minutes to hours. There is currently no method of predicting when or where a solar flare might occur, although they exclusively happen in the vicinity of sunspots. Flares are also associated with Coronal Mass Ejections (CMEs), which are ejections of material from the corona, often towards the earth.

While some flares are energetic enough to cause damage to satellites or even entire power grids [1], these events are rare, though not unheard of. So aside from studying the Sun to better understand physical processes going on in the universe, we have good reason to understand the star that has such an effect on us.

Solar Radio Emission

Radio emission from the Sun during a solar flare can be caused by gyrosynchrotron radiation. Gyrosynchrotron radiation[5][4] is the process in which non-relativistic electrons together with free protons and ions in plasma experience the Lorentz force and spiral around magnetic field lines. Gyrosynchrotron radiation is proportional to magnetic field strength and the orientation of that magnetic field, unlike X-ray emission processes. Many other processes such as cyclotron maser radiation and plasma radiation can cause radio emission, but have not yet been seen to play a major role in the structure of solar flares[9].

Solar X-ray Emission

X-ray emission from the Sun is caused by many different processes. The process we are most interested in are non-thermal bremsstrahlung[4], also called braking radiation, and thick target radiation, or non-thermal free-free radiation. In this process, non-relativistic electrons, free protons and ions are smashed into a "thick target" (for our purposes the dense plasma on the surface of the Sun). This process will only produce Hard X-rays (greater than 10 KeV) and perhaps low energy gamma rays. X-ray emission from the Sun is also caused by thermal bremsstrahlung and coherent plasma radiation, but these processes have not been shown to be correlated to radio emission from solar flares.

Correlation between Radio and X-ray Emission

It may not be immediately obvious why there could be a correlation between radio and X-ray emission – what single process could produce both low and high energy emission at the same time? It turns out that there are multiple processes that utilize the same pool of non-relativistic electrons populating a solar flare. An electron gyrating around a magnetic field line that spans two sunspots in a flaring region causes the radio emission, and when this electron then smashes into the surface of the Sun, it produces X-ray emission (Figure 2) [3][5]. Most correlation between radio and X-ray emission takes place in very energetic solar flares, however some correlations have been observed in micro flares which are flares with energies about one millionth that of a regular flare[5].

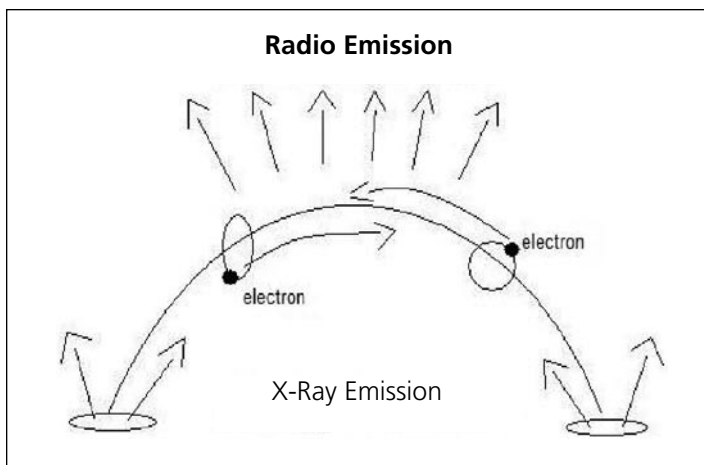


Figure 2: Depiction of Radio and X-ray Emission on the Sun

METHODOLOGY

The Small Radio Telescope

BSC's Small Radio Telescope (SRT – Figure 3), has a 2.3 meter dish, and is housed on the roof the Conant Science Building. It was developed at M.I.T's Haystack Observatory in Westford MA as an undergraduate research tool and measures radio flux in the L-Band (1.42 GHz) [11]. We started our



Figure 3: The Small Radio Telescope at Haystack Observatory (Courtesy of Haystack.MIT.edu)

project by observing the Sun at 1420 MHz, but then switched to 1415 MHz so our data would be consistent with previous observations made at MIT.

The SRT takes observations by measuring the power received, which is proportional to the temperature of the source, and comparing it to the power output of an internal resistor, which is proportional to antenna temperature (or the temperature measured at the resistor[6].) The ratio of the power from the source and the power output of the resistor is proportional to brightness temperature of the source. So, in short, the SRT measures the intensity of the radio emission from a source and converts this signal to the brightness temperature, reported in Kelvin. The details of this conversion are worked out below.

First Planck's law is used to infer the brightness temperature of a source:

$$B_{\nu}(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

Where $B_{\nu}(T)$ is the Brightness temperature with respect to a frequency, ν is the frequency, h is Planck's constant, k is Boltzmann's constant, T is the physical temperature in Kelvin, and c is the speed of light. Integrating over all frequencies,

$$B(T) = \frac{2h}{c^2} \int_0^{\infty} \frac{\nu^3}{e^{h\nu/kT} - 1} d\nu \quad (1)$$

We find:

$$B(T) = \frac{2h}{c^2} \left(\frac{kT}{h} \right)^4 \left(\frac{\pi^4}{15} \right)$$

If we condense all the constants into σ , equation (1) becomes:

$$B(T) = \sigma T^4 \quad (2)$$

Equation (2) states that the brightness temperature of a source is proportional to its actual temperature.

Now we convert the brightness temperature $B(T)$ to power measured in the resistor in the SRT. The basic definition of power is

$$Power = VI = I^2 R = \frac{V^2}{R} \quad (3)$$

Where V is potential difference (voltage), I is current, and R is resistance. The power in the resistor in the SRT will be reduced by a factor of 1/2 because of the polarization of the dish, which means that the receiver is only collecting half of the power provided by the radio waves, and another 1/2 by taking the time average of V , which accounts for how voltage we measure varies with time, so equation (3) is now:

$$P = \frac{V^2}{4R} \quad (4)$$

A random walk analysis is a mathematical model that can be used to approximate the fluctuations in the voltage V . If we apply a random walk analysis to V^2 , we find:

$$V^2 = 4RkT_B$$

Where T_B will now be used to represent brightness temperature. Substituting V^2 into equation (4) we find:

$$P_{Resistor} = kT_B \quad (5)$$

The power provided by a radio source is given[6]:

$$P_{RadioSource} = \frac{SA}{2} \quad (6)$$

Where S is the signal strength in Janskys, A is the area of the telescope, and factor of 1/2 because we measure only left or right polarization.

The change in temperature at the resistor is proportional to the ratio of the power from a radio source and the power at the output of the resistor[10].

$$\Delta T = \frac{P_{RadioSource}}{P_{Resistor}}$$

The software provided with the SRT does these calculations for us and reports the temperature of the radio source in Kelvin. Plotted as a function of time, these data show the daily radio flux of the Sun.

The SRT has a built in calibration system which reduces the background noise from the internal temperature variations of the SRT[11]. We made observations for 10 weeks between May 27 and August 6, 2009, excluding weekends. Most data were taken between 9 a.m. and 4 p.m.

X-ray Data

The National Oceanic and Atmospheric Administration (NOAA) has dedicated several Geostationary Operational Environmental Satellites (GOES) to solar and space weather observations. GOES-10 is, along with other operations, dedicated to looking at the Sun and measuring the X-ray flux at .05-.04 nm and .1-.8 nm wavelengths with 1 and 5 minute resolutions. These data are available free to the public via the NOAA website. GOES-10 was scheduled to be decommissioned in December 2009 because its propulsion fuel will have run out. NOAA has not yet announced which GOES satellite will take over the solar X-ray flux monitoring duty.

Analysis

Daily data analysis was done by comparing the radio flux obtained from the SRT and the GOES-10 X-ray 1 minute average data in Excel. B.S.C.'s weather station, which measures the flux from the Sun in the visible spectrum, provided data that were used to account for intensity fluctuations due to atmospheric interference.

Results

For each day we made observations, radio data from the SRT and X-ray data from NOAA were plotted in Excel as a function of time.

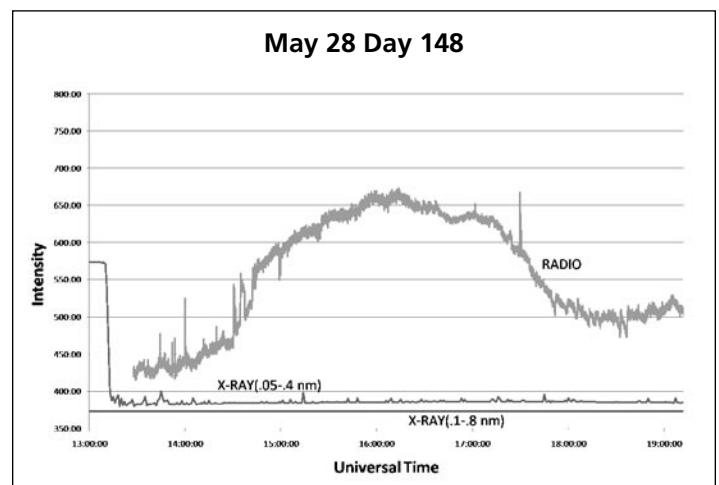


Figure 4: May 28, 2009 Radio activity with little to no X-ray activity.

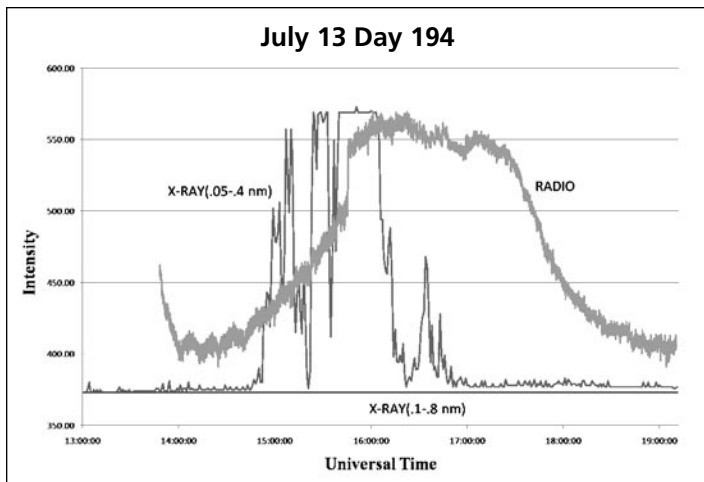


Figure 5: July 13, 2009 X-ray activity with little to no radio activity. Increase in radio at the start of the day is addressed in the Discussion Section.

Figure 4 is an example of a day where there was radio activity (notice the spike at 17:30) and little or no X-ray activity. The radio activity on this day could be attributed to micro flares, which are happening all the time on the Sun[3]. However it could also be explained by the presence of heavy thunderstorms in the region. On several days observations showed that there was X-ray activity but no radio activity as shown in Figure 5. The reason for this X-ray activity absent of radio activity could be because the mechanism for the energy release was something other than non-thermal bremsstrahlung such as synchrotron radiation or plasma radiation. If this is the case then there would be no expectation of a radio correlation.

The data also show small fluctuations at the beginning and end of the day, a signature that appeared during the same time period each day we observed. We concluded that these fluctuations were not due to variations of the Sun but rather terrestrial interference or issues related to the SRT.

The rise in fluctuation intensity during the middle of every day – the overall “hump” – is also evident in each daily observation. When the SRT data were compared with B.S.C.’s weather observatory, which measures the Sun’s intensity in the visible spectrum, we found that both spectrum intensities peaked in the middle of the day. This correlation suggests that when the Sun is lower in the sky, radio wavelengths – as well as visible - are being attenuated as they propagate through more atmosphere. Another explanation for this “hump” could be that the SRT heats up as the Sun gets higher in the sky, and the heat generated by the electronics could increase the gain in the receiver, resulting in a rise in intensity.

Because of these issues, we chose to narrow our search for correlated events to between 10 AM and 2 PM. Any events detected during this time frame were not affected by the “hump” since the events are over a time scale where there is no significant change in the background emission.

Of the 21 days we recorded activity, 5 showed X-ray events only, 5 showed radio events only, and 11 days had both X-ray and radio events – though only one of those events, a solar flare, had correlated X-ray and radio emission.

Because the Sun is in solar minimum, we did not expect to observe many solar flares, however we were fortunate to observe one. NOAA detected a C1 class solar flare at 16:59 on Day 187 Universal Time emerging from sunspot 11024. This sunspot also erupted with a C2-class flare the previous day, but our SRT was not making observations during the event. The NOAA classifies solar flares by their peak energy output in the 1-8 Angstrom spectrum. A C-class solar flare is classified as such because its’ peak energy is between and $Watts/m^2$. This was a C1 flare because it had the lowest output energy possible to be defined as a C-class flare.

The radio and X-ray data for this event are shown in figure 6. At the impulsive phase of the flare, we see a peak in radio, followed by a peak in X-rays, indicating that the electrons in the flaring region were rotating around magnetic field lines first, then accelerating into the solar surface, producing X-rays. After the impulsive phase in both energies, there is prolonged radio emission even after the X-rays decay. This suggests that perhaps more electrons were ejected from the solar surface and subsequently rotated around the magnetic fields for an extended period of time.

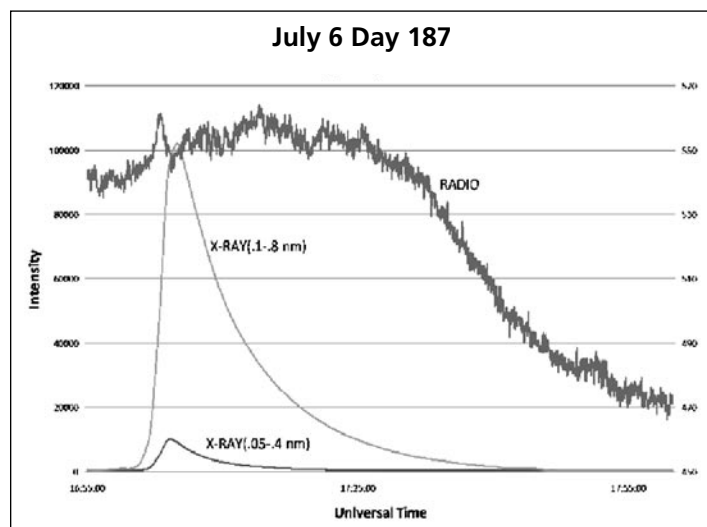


Figure 6: July 6, 2009 C-1 Class Solar flare recorded by the NOAA from sunspot 11024.

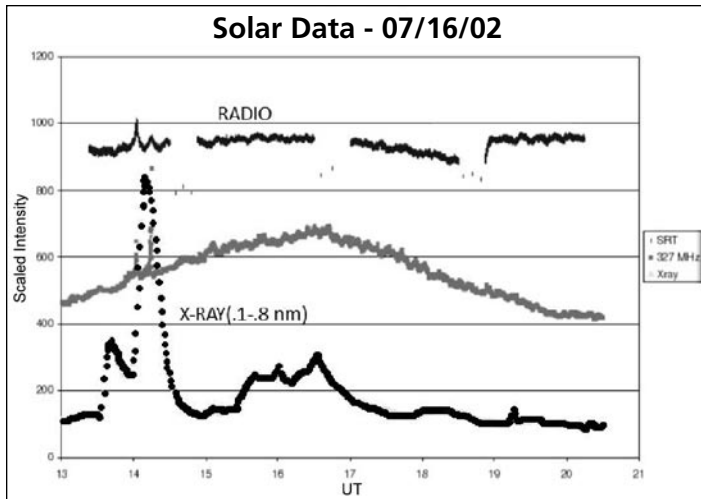


Figure 7: July 16, 2002 Haystack Observatory Recorded a Similar Correlation between Radio and X-ray Emission. (Courtesy of Haystack.MIT.edu)

In 2002, MIT's SRT was used to observe the Sun during solar maximum, and they observed six correlated events. Figure 7 is an example of one such event[11]. Notice the small intensity rise in radio just before the peak in X-ray, similar to what we observed in figure 6. Note that the radio data at 327 MHz was recorded by Haystack Observatory's 37 meter radio telescope.

Discussion and Conclusion

We observed the Sun during solar minimum and did not expect to observe many flares. However, we hoped that if we did observe a flaring event, we could also observe correlated emission between radio and X-rays. Fortunately, we did.

The correlated emission from the C-class flare on July 6, 2009, suggests that non-thermal electrons were gyrating around magnetic field lines and impacting the solar surface. For those events where only X-ray emission was detected, it is likely that the population of electrons responsible for the X-ray emission were not non-thermal, and therefore would not produce radio emission in ranges detectable by the SRT. Those events where only radio emission was detected could be due to micro flares, which are solar flares with much less energy and no X-ray component[3][5]. Another possibility is that they are just coincidental fluctuations due to normal solar activity.

With this work, we were able to show that we can observe solar flares with B.S.C.'s SRT, and that the one flare we observed did in fact correlate with X-ray emission. Our results suggest that if we continue to monitor the Sun as we head into solar maximum, we have the ability to observe more solar flares. We also observed small radio events with no X-ray correlation, events which were observed with MIT's SRT during solar

maximum. These events are intriguing, possibly due to micro flares, and may be the basis for future work.

Acknowledgments

I would like to thank my mentor Dr. Martina Arndt for all of her expertise and guidance during this project. I would also like to thank Dr. Phil Shute for providing assistance with the operation of the SRT; Dr. Rob Hellstrom for providing the solar radiation data from the B.S.C. Weather Station; Jim Munise for help with setting up the SRT, and M.I.T. Haystack Observatory. I would also like to thank the Adrian Tinsley Program for giving me this great opportunity.

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