AFRL-AFOSR-VA-TR-2018-0293

Filament eruptions and the solar radio F10.7 flux

R.T. James McAteer
New Mexico State University
1620 Standley Dr Academic RESH A RM 110
Las Cruces, NM 88003-1239

08/01/2018
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/RTB1

DISTRIBUTION A: Distribution approved for public release.

Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01-08-2018	Final Performance	15 Nov 2014 to 14 Nov 2017

4. TITLE AND SUBTITLE
Filament eruptions and the solar radio F10.7 flux

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-15-1-0014

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
R.T. James McAteer

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
New Mexico State University
1620 Standley Dr Academic RESH A RM 110
Las Cruces, NM 88003-1239 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2018-0293

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Objective 1: Determine whether the presence of, or changes in, an H filament can be used to infer properties of a flare-CME. This studied whether the actual presence of a filament can be used to assist in predicting future flare-CME events. It searched for a correlation between the physical properties of the filament (e.g., length, shape), changes in these properties prior to a flare-CME event, and measures of event strength (e.g., CME speed, CME kinetic energy, presence of a Moreton wave).
Objective 2: Create high spatial resolution images of the Sun at 10.7cm.

15. SUBJECT TERMS
Sun, CME, EUV Imaging

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			MOSES, JULIE
Unclassified	Unclassified	Unclassified	UU		19b. TELEPHONE NUMBER *(Include area code)* 703-696-9586

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

AFOSR Final Report

AWARD NUMBER: FA9550-15-1-0014
AWARD TITLE: Filament eruptions and the solar radio F10.7 flux

Statement of Objectives

The goal of this proposal was to carry out fundamental research into a causal link between features and events on the Sun, and in-situ measurements in the near-Earth environment.

This proposal focused on an understanding of (i) the coupled flare-coronal mass ejection (CME) system and (ii) the origins of the solar F10.7 radio flux in order to improve our readiness level in protecting our space-based assets from adverse space weather effects. The study of the coupled Sun-Earth system will provide a better physical understanding of the Sun's atmosphere, relevant to any space weather prediction service

The overall goal was met by addressing 4 objectives.

• Objective 1: Determine whether the presence of, or changes in, an Hα filament can be used to infer properties of a flare-CME. This studied whether the actual presence of a filament can be used to assist in predicting future flare-CME events. It searched for a correlation between the physical properties of the filament (e.g., length, shape), changes in these properties prior to a flare-CME event, and measures of event strength (e.g., CME speed, CME kinetic energy, presence of a Moreton wave).
• Objective 2: Create high spatial resolution images of the Sun at 10.7cm. The Expanded Very Large Array and the Expanded Owens Valley Solar Array was used in order to identify the sources of F10.7 and their emission mechanisms. This created F10.7 images with spatial resolution better than 20″, sufficient to distinguish sunspot, active region loops, plage and network sources.
• Objective 3: Identify the most appropriate technique for creating differential emission measure maps from EUV images. The EUV data was used to generate full sun Differential Emission Measure (DEM) maps (Plowman et al. 2013) This provided information on the amount of coronal plasma as a function of temperature, which was then be used to predict the 10.7 cm radio signal from Bremsstrahlung emission.
• Objective 4: Investigate the relative contributions of Bremsstrahlung and gyro-resonance emission to the solar F10.7 radio flux. Although both emission mechanisms are known to contribute to F10.7, their relative contributions have never been able to be determined. Bremsstrahlung arises from the same plasma that produces soft X–ray and extreme ultraviolet wavelengths, while gyro-resonance at 2.8 GHz requires magnetic field strengths of at least 300 G in the corona.

This proposal contains no proprietary information. It will perform basic research in the scientific community for the greater good of the general public. Although there is no substantial involvement between the Department of Defense and the recipient, it will complement the work of Dr Balasubramaniam and Dr White at the Air Force Research Laboratory, Albuquerque.

J. McAteer - Principal Investigator – New Mexico State University

Research Objectives completed

Overview

The Sun's variability has dramatic impacts on the structure and behavior of the Earth's atmosphere and local space weather. The most spectacular small scale variations in time and space are solar eruptive events. Originating in coronal active regions (which manifest on the solar surface as sunspots), these events produce high energy extreme ultraviolet (EUV) emission associated with a solar flare and charged particles due at least in part to associated coronal mass ejections (CMEs). The occurrence of a flare-CME event is often related to the existence of, changes in, or disappearance of a solar filament (Zuccarello et al. 2014). *The first research objective in this proposal seeks to study solar filaments and their relationship to flare-CME events*.

The occurrence rate of these events peaks every 11 years as a function of the solar cycle. The radio emission at a wavelength of 10.7 cm (F10.7) is one of the key indices used to measure this solar activity. It can be used as a proxy of the total solar EUV emission responsible for the structure of the Earth's ionosphere, but which cannot be observed from the ground. The F10.7 dataset consists of daily observations since 1947 (Chen et al. 2011), and is used as an input in a wide variety of models designed to predict the effects of space weather on the near Earth environment. *The final three objectives of this proposal seek to study the F10.7 emission and its physical causes.*

Objective 1: Determine whether the presence of, or changes in, a Hα filament can be used to infer any properties of a flare-CME.

We completed a comprehensive literature search, including a search for current and out-of-date filament catalogs. This was primarily carried out by team member Dr Zhu and will provide the basis of the future work and define the specific science goals for this objective. Under the instruction of Dr Zhu, team member Rerocchis obtain Hα data for the selected events and completed a list of catalogued filaments and flare-CME events. These include solar flares with and without CMEs as well as CMEs without an associated flare. The basic properties of the flares (size, location, active region properties, etc.) and CMEs (angular extent, speed, acceleration, position angle, etc.) were extracted from existing databases.

Objective 2: Create high spatial resolution images of the Sun at 10.7cm

Graduate student Schonfeld completed a comprehensive literature search, including a search for current and past attempts at imaging the Sun in the F10.7 emission. This literature search will provide the basis of the future work and define the specific science goals for this objective. An existing EVLA observation of full–disk F10.7 emission was fully reduced and analyzed to separate the contributions of gyro-resonance and bremsstrahlung emission. These data covers the full 2-4 GHz frequency range. These are the first full–disk images of the Sun in this frequency range with sub–arcminute spatial resolution.

Objective 3: Identify the most appropriate technique for creating differential emission measure maps from EUV images.

Graduate student Schonfeld completed a comprehensive literature search, including a search for current and past attempts at DEM analysis. This literature search will provide the basis of the future work and define the specific science goals for this objective. We have identified an optimal technique for deriving DEMs from the AIA images. We reduced SDO-AIA data to a spatial resolution of 4.8 arc seconds to speed up the process and examined all possible combinations of inversion parameters. We used the DEM to recreate the EUV images and used these to predict the bremsstrahlung component of the radio emission.

Objective 4: Investigate the relative contributions of Bremsstrahlung and gyro-resonance emission to the solar F10.7 radio flux.

A test study was performed using a set of EUV images from the Atmospheric Imaging Assembly to compute differential emission measures (DEMs, a measure of the plasma thermal content) that are used to predict an $F_{10.7}$ bremsstrahlung image. This is compared with an imaging observation of $F_{10.7}$ taken with the Very Large Array and proves the ability to identify both bremsstrahlung and gyroresonance emission with DEMs. Using the lessons from this initial analy- sis, four years of full-Sun DEMs are computed from EUV Variability Experiment spectra. This reveals an unexpected temporal bimodality in the coronal ther- mal structure. These DEMs are used to predict the bremsstrahlung emission at five microwave frequencies including $F_{10.7}$ and then the relative contribution of bremsstrahlung and gyroresonance emission is determined both spectroscopically and using the DEM predictions. Bremsstrahlung emission is found to dominate the coronal $F_{10.7}$ except during short periods of intense activity near solar max- imum. A bremsstrahlung correction to $F_{10.7}$ is calculated and compared to the traditional $F_{10.7}$ proxy, revealing the fundamental limitation of its efficacy as a single-input EUV proxy.

Meeting the public purpose

As human reliance on technology increases, so does the potential for geo-effective solar storms with catastrophic consequences and the need to anticipate space weather effects. Coronal mass ejections with filaments are source of the most geo-effective storms and F10.7 is one of the most widely used inputs for space weather modeling. By improving the understanding and modeling of CMEs and the F10.7 radio flux, we improved on our ability to predict the Sun's effect on the near Earth environment. As such, the basic research proposed here will have specific applications in a number of areas where the structure of the ionosphere is important, such as satellite communications and operations, navigation, and radar.

Potential relationship of the proposed research, and development, to the Department of Defense.

The Dod mission is *'...to protect the security of our country*' .This proposal sought to contribute to this mission by significantly enhancing our space weather prediction capabilities in protection of our space-based assets. It provided a graduate student and postdoctoral researcher with research experience relevant to space weather. This proposal directly addressed the goals of Space Sciences in the AFOSR as defined in the Broad Agency Announcement BAA-AFOSR-2014-0001 under Quantum and Non-equilibrium process, through fundamental research on the solar-terrestrial environment including the stated stated basic research objectives of

"The mechanism(s) heating the solar corona and accelerating it outward as the solar wind"

"The triggers of coronal mass ejections (CMEs), solar energetic particles (SEPs), and solar flares" and

"The variations in solar radiation received at Earth and its effects on satellite drag."

Personnel effort (including PI effort)

Principal Investigator (PI) time -

Dr McAteer assumed overall responsibility for scientific success of the work and ensuring appropriate progress at each stage of the project. He led weekly meetings with all NMSU members of the group. Dr McAteer identifying all team members and incorporated them into the existing solar group at NMSU, ensuring their scientific progress in research and appropriate coursework, and acting as supervisor and mentor. Dr McAteer performed these responsibilities as part of his normal academic duties.

Other team member time -

Dr Zhu, Dr Wang, and Student deRocchis had prime responsibility for the CME-filament project (objective 1) and all the tasks identified therein.

Graduate student Sam Schonfeld led the task in Obj 2, 3 and 4. He finished all his coursework and thesis proposal in Yr1. He presented this work at conferences and was the lead author on two papers resulting from this research. This work provide the subject matter for Sam to complete his PhD in solar physics. Sam received 9 months FTE (at 50% commitment) and Dr McAteer provided summer funding and travel funds at no cost to this proposal

Summary

Through a series of carefully planned objectives, the goal of this project proposal was to *carry out fundamental research into a causal link between features and events on the Sun, and in-situ measurements in the near-Earth environment.*. By focusing on two specific science questions (the role of filaments in CMEs and the origins of the F10.7 radio flux) relevant to the larger community effort, we will enhance research in space weather vital to the the DoD. The scientific and technical plan contributed directly to the DoD mission while developing new a new research base in space weather. The PI and key personnel were carefully selected to provide the scientific and education collaborations and skills vital for this research to complement the work of Dr Balasubramaniam and Dr White at the Air Force Research Laboratory, Albuquerque. All tasks are completed as identified in the proposal.