(NASA-CR-174034) STUDY OF THE SOLAR CORONA USING RADIO AND SPACE OBSERVATIONS Annual Status Report, Nov. 1983 - Oct. 1984 (Colorado Univ.) 37 p HC A03/MF A01 CSCL 03B G3/92

N85-11963

Unclas 24299

ANNUAL STATUS REPORT

November 1983 - October 1984

Grantee:

The Regents of the
University of Colorado
Boulder, Colorado 80309

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Grant Title:

Study of the Solar Corona Using
Radio and Space Observations

Grant Number:

NASA Grant No. NSG-7287
Univ. of Colorado No. 1-5331-26

This annual report was prepared by the principal investigator under grant no. NSG-7287 from the National Aeronautics and Space Administration.

CONTENTS

Annual Report

STUDY OF THE SOLAR CORONA
USING RADIO AND SPACE OBSERVATIONS

NASA Grant NSG-7287

In the following we detail the progress made under the three main areas of investigation: 1) the physics of coronal transients, 2) the characteristics of radiation and accelerated particles at the time of flares, and 3) the density-temperature structure of the transition region and corona and the coronal magnetic field.

1) The Physics of Coronal Transient Events

Together with the HAO group led by L. House and the Australian group led by K. Sheridan, Graduate Student Dale Gary and I performed a detailed analysis of a coronal transient event that was particularly well observed by the C/P experiment on SMM and the Culgoora Radio Observatory. The analysis and interpretation composed part of Gary's thesis which is now complete; he is presently a Research Associate at Caltech. One part of this work, the part related to shock waves and Type II bursts, has recently been published. The main results are given in the attached abstract.

The second part of this work involved one of the first quantitative analyses of SMM C/P observations of brightness, and simultaneous radio observations of a moving Type IV radio source. The emphasis was placed on identifying whether the radio emission was due to gyrosynchrotron radiation or plasma radiation, and on whether the observations could distinguish between "loop" and "bubble" models of transients. The results have been submitted for publication and are given in the attached abstract.

Analysis of another event is underway, led by Graduate Student Joe Bassi and Bill Wagner of HAO. A report on the preliminary results of this work was presented at the SMM workshop.

2) The Characteristics of Radiation and Accelerated Particles At the Time of Flares

We have reported on the radio and hard X-ray characteristics of two flares observed with several instruments: the VLA, ground-based radiometers, and hard X-ray spectrometers and imaging devices on spacecraft (SMM, ISEE-3 and Hinatori). One flare (Dulk, Bastian and Hurford 1983; see attached abstract) demonstrated that large source sizes and inhomogeneous structures are likely in a large flare, while the other (Dulk, Bastian and Kane 1985; see attached abstract) established the altitudes of microwave sources in two limb flares, and again emphasized the inhomogeneous nature of impulsive flare sources.

The mechanism of amplified decimetric waves was proposed by Melrose and Dulk (1982a, 1982b; see attached abstracts) as an energetically important radiation source in flares. We are continuing to investigate both the maser mechanism and its consequences. Part has been published (Dulk and Melrose 1983; Melrose and Dulk 1984; see attached abstracts), and part is to be included in the chapter on energy transport of the SMM Workshops. Observationally we set the VLA to search for very small, very bright sources expected from this mechanism; so far we have not been successful in observing any flares. Theoretically, mainly under the auspices of our STTP grant, we are considering whether absorption of the maser radiation in small scale pockets in the corona can account for the very broad ion lines (e.g. Ca XIX) observed by XRP and other instruments aboard spacecraft.

We now have substantial evidence that our maser mechanism is important on stars other than the Sun, notably flare stars and AM Herculis type binaries (see attached abstracts by Dulk et al. 1983). On some stars the flares are of much greater magnitude than on the Sun, but many of the physical processes are undoubtedly the same. So far we are using knowledge gained form solar studies to help us understand processes on those stars; hopefully some processes will stand out more clearly in the different environment of stars and we will be able to transfer this knowledge back, to help us understand the Sun better.

In the larger heliosphere, we have undertaken a series of studies of radio bursts in the solar wind, bursts observable only at low frequencies (less than a few MHz) aboard spacecraft. In particular, we have collaborated with investigators of the Goddard/French radio experiment on ISEE-3 and used much of that data together with simultaneous data from Culgoora. Results obtained to now include investigation of propagation effects (ducting and scattering of radio waves by the inhomogeneous interplanetary medium), and whether the radiation is due to plasma emission at the fundamental or harmonic (see attached abstracts). Work is continuing on further analysis of data with particular emphasis on describing the small scale structures in the solar wind.

3) The Density-Temperature Structure of the Transition Region and Corona and The Coronal Magnetic Field

Our interest is unabated in trying to reconcile or understand the reasons that models of the transition region and low corona based on EUV vs. radio observations differ so widely. On past occasions we have attempted to use the VLA to map the Sun simultaneously with rocket flights (of LASP) which measured EUV line intensities. On two occasions the rocket flights were postponed. We were finally successful in June 1984, when we obtained simultaneous, successful observations, not only with the rocket and the VLA, but with the 300' telescope at Green Bank, West Virginia. Data analysis is progressing, with preliminary reductions being very promising.

One of our previous VLA observations resulted in an exceptionally fine radio picture of the Sun at 1.4 GHz that shows active regions, coronal holes, filament cavities and quiet regions (Dulk and Gary 1983; see attached abstract). In general appearance it is much the same as when observed in soft X-rays. In addition, the measured degree of circular polarization provides a means of estimating the coronal field strength in certain parts of active regions, to altitudes of about 50,000 km. The inferred values in the outer parts of several active regions are in the range of 25 to 100 gauss, and the polarity is the same as on photospheric magnetograms. When this technique can be used with simultaneous measurements of soft X-ray brightness, both the density and field strength can be estimated as a function of height. Also, we have observed the Sun with the VLA in a more widespread configuration in order to obt in even better resolution, and data analysis on this is progressing.

APPENDIX A

LIST OF RECENT PAPERS

Slee, O.B., Sheridan, K.V., Dulk, G.A. and Little, A.G., 1983, "Maps of Centaurus A from Molonglo and Culgoora", Proc. Astron. Soc. Australia, 5, 247-251.

Hewitt, R.G., Melrose, D.B. and Dulk, G.A., 1983, "Cyclotron Maser Emission of Auroral Z-mode Radiation", J. Geophys. Res., 88, 10065-10071.

White, S.M., Melrose, D.B. and Dulk, G.A., 1983, "Electron Cyclotron Masers During Solar Flares", Proc. Astron. Soc. Australia, 5, 188-191.

Dulk, G.A., 1984, "The Solar Atmosphere, Magnetic Fields and Activity", Chapter 2 in Solar Radiophysics, D.J. McLean, ed., Cambridge Univ. Press, submitted.

Dulk, G.A., McLean, D.J. and Nelson, G.J., 1984, "Solar Flares", Chapter 4 in Solar Radiophysics, D.J. McLean, ed., Cambridge Univ. Press, submitted.

Suzuki, S. and Dulk, G.A., 1984, "Bursts of Type III and Type V", Chapter 12 in Solar Radiophysics, D.J. McLean, ed., Cambridge Univ. Press, submitted.

Gary, D.E., Dulk, G.A., House, L., Illing, R., Sawyer, C., Wagner, W.J., McLean, D.J. and Hildner, E., 1984, "Type II Bursts, Shock Waves, and Coronal Transients: The Event of 1980 June 29, 0233 UT", Astron. Astrophys., 134, 222-233.

Dulk, G.A., McLean, D.J., Manchester, R.N., Ostry, D.I. and Rogers, P.G., 1984, "Image Restoration Techniques--How Good are They?", Indirect Imaging, ed. J.A.Roberts, (Cambridge: Cambridge University Press), pp. 355-361.

Dulk, G.A., 1984, "Radio Wave Heating in Impulsive Flares, Shock Waves, and Coronal Mass Ejections", in STIP Symposium on Solar/Interplanetary Intervals, Eds. M.A. Shea, D.F. Smart and S.M.P. McKenna-Lawlor, (Chelsea, Mich.: Book Crafters Inc.), pp. 331-336.

Dulk, G.A., Suzuki, S. and Sheridan, K.V., 1984, "Solar Noise Storms: The Polarization of Type III and Related Bursts", Astron. Astrophys., 130, 39-45.

Melrose, D.B., Hewitt, R.G. and Dulk, G.A., 1984, "Electron-Cyclotron Maser Emission: Relative Growth and Damping Rates for Different Modes and Harmonics", J. Geophys. Res., 89, 897-904.

Melrose, D.B. and Dulk, G.A., 1984, "RF Heating of the Solar Corona During Flares", Astrophys. J., 282, 308-315.

Dulk, G.A., 1984, "Activity and Magnetic Fields on Stars from Radio Observations", Proc. Japan-France Seminar on Active Phenomena in the Outer Layers of the Sun and Stars, J.C. Pecker and Y. Uchida, eds., (Paris: Centre National de la Recherche Scientifique), pp. 91-95.

Steinberg, J.L., Dulk, G.A., Hoang, S., Lecacheux, A. and Aubier, M., 1984, "Type III Bursts in the Interplanetary Medium: The Role of Propagation Effects", Astron. Astrophys., in press.

Dulk, G.A., Steinberg, J.L. and Hoang, S., 1984, "Type III Bursts in the Interplanetary Medium: Fundamental or Harmonic", Astron. Astrophys., in press.

Gary, D.E., Dulk, G.A., House, L.L., Illing, R., Wagner, W.J. and McLean, D.J., 1984, "The Type IV Burst of 1980 June 29, 0233 UT: Gyro-Synchrotron or Harmonic Plasma Emission?", submitted to Astron. Astrophys.

Hoang, S., Steinberg, J.L. and Dulk, G.A., 1984, "Sizes and Positions of Interplanetary Type III Bursts", to be submitted to Astron. Astrophys.

Dulk, G.A. 1985, "Solar Research", in Trans. IAU, Reports on Astron., Commission 40, ed. K. Kellermann, in press.

APPENDIX B

Invited Talks and Colloquia (1983-84)

"Electron Cyclotron Masers", CSIRO (Australia) colloquium, March 1983. "Plasma Phenomena in Close Binary Stars", Dept. of Theoretical Physics, U. of Sydney, colloquium, March 1983.

"AM Herculis Type Binaries", CSIRO (Australia) seminar, April 1983. "Solar Flares Observed with the VLA", CSIRO (Australia) seminar, May 1983.
"Masers Operating in Solar and Stellar Flares", CSIRO (Australia) seminar, June 1983.

"The Radio Frequency (Maser) Heating Model of Flares", Space Research Institute (Utrecht), October 1983.

"Electron Cyclotron Masers in the Sun and Stars", Observatoire de Paris seminar, October 1983.

"Stellar Radio Astronomy", ETH seminar, Zurich, Switzerland, November 1983.

"Maser Operation in the Planets, Sun and Stars", University of Bern colloquium, Bern, Switzerland, November 1983.

"RF Heating as a Means of Energy Transport During Flares", SMM Workshop, Goddard, February 1984.

"Cyclotron Masers in Astronomy and in RF Heating in Flares", Astro- physical, Planetary and Atmospheric Sciences Colloquium, University of Colorado, May 1984.

"Electron-cyclotron Masers and their Astronomical Manifestations", Dept. of Physics, Colorado School of Mines, October 1984.

Contributed Papers (1983-84)

"Heating of the Corona by Masers in Solar Flares", G.A. Dulk, SMM Workshop, Goddard, January 1983.

"Electron Distribution Functions in Solar Flares", S.M. White, D.B. Melrose and G.A. Dulk, Meeting of Astron. Soc. Australia, May 1983. "Low Frequency Observations of Centaurus A", O.B. Slee, A.G. Little, K.V. Sheridan and G.A. Dulk, Meeting of Astron. Soc. Australia, May 1983.

"Image Restoration Techniques", G.A. Dulk, D.J. McLean, R.N. Manchester, D. Ostry, and G. Rogers, IAU Image Processing Symposium, Sydney, September 1983.

"Recent Radio Observations of Activity and Magnetic Fields in Stars", G.A. Dulk, Japan-France Seminar, Paris, October 1983.

"Radio Emission from AM Herculis: Spectrum and Temporal Variations", T.S. Bastian, G.A. Dulk and G. Chanmugam, Workshop on Cataclysmic Variable Stars, Baton Rouge, La., February 1984.

"Damping of the Magnetoionic Z-mode in Solar and Stellar Flares", S.M. White, D.B. Melrose and G.A. Dulk, Stellar Radio Continuum Workshop, Boulder, Colorado, August 1984.

"Radio Emission from the Magnetic Cataclysmic Variable AM Herculis", T.S. Bastian, G.A. Dulk and G. Chanmugam, Stellar Radio Continuum Workshop, Boulder, Colorado, August 1984.

"Type III Solar Radio Bursts", G.A. Dulk, Plasma Physics Seminar, University of Colorado, October 1984.

Conferences Attended and Other Grant-Related Activity (1983-84)

Distinguished Visiting Scientist, CSIRO, Australia, January-June 1983. Senior

Visiting Scientist, Observatoire de Paris, France, July-December 1983.

Attended SMM Workshop, Goddard Space Flight Center, January 1983.

Attended UK/SMM Workshop, U. of Oxford, England, September 1983.

Visited Dept. of Applied Mathematics and Mullard Radio Astronomy Observatory, U. of Cambridge, England, September 1983.

Visited Rutherford-Appleton Laboratories, Didcot, England, September 1983.

Visited Space Research Laboratory, Utrecht, Netherlands, October 1983.

Attended meeting of Japan-France Seminar, Paris, October 1983.

Visited Dept. of Applied Physics, University of Bern, Switzerland, November 1983.

Site visit to NRAO Tucson, Az., January 1984.

Attended SMM Workshop, Goddard SFC, February 1984.

Attended workshop on cataclysmic variable stars, LSU, Baton Rouge, La., February 1984.

Conducted observing program on cataclysmic variable stars, VLA, March 1984.

Scientific Organizing Committee for Stellar Continuum Radio Workshop, January-August 1984.

Conducted observing program on flare stars in Orion and the Pleiades, VLA, March 1984.

Meeting of NRAO Visitors Committee, Charlottesville, Virginia, April 1984

Meeting of NASA Solar Physics Advisory Group, Lanham, Maryland, April 1984.

Meeting of NRAO Users Committee, Socorro, NM, May 1984.

Attended General Assembly of COSPAR, Graz, Austria, June 1984.

Conducted joint EUV rocket and VLA radio experiment, June 1984.

Invited working visit to Observctoire de Paris, Meudon, June-July 1984.

Attended Workshop on Stellar Continuum Radio Astronomy, Boulder, Colorado, August 1984.

Conducted VLA observations of the Sun, August 1984.

Site visit to Clark Lake Radio Observatory for NSF, September 1984.

Meeting of NASA Solar Physics Advisory Group, Lanham, Maryland, September 1984.

APPENDIX C

Abstracts of Papers Published, Submitted or Prepared During the Previous Year and the Present Year of Grant NSG-7287

DUAL FREQUENCY OBSERVATIONS OF FLARES WITH THE VLA

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ABSTRACT

We describe observations of three flares made at 5 and 15 GHz with the VLA, two subflares near the limb on 1981 November 21 and 22, and an M7.7 flare on 1981 May 8. Even though the time histories of the November flares indicated simple impulsive bursts, the VLA observed no 5 GHz radiation at all from one flare, and from the other, the 15 GHz radiation emanated from a source which was smaller, lower and displaced from the 5 GHz source. Without the spatial information, we would have derived incorrect results from the assumption that photons of different energy (both at X-ray and radio wavelengths) arose from one homogeneous volume.

The 1981 May 8 flare was intense and complex, having two or more sources at both 5 and 15 GHz. Prior to the peak of the flare, the sources grew in size to > 20" to 40", after which they were not visible to the VLA; only (weak) subsources could be seen. These were located between or at the edge of the Hα ribbons and the two hard X-ray sources imaged by the Hinatori. Highly polarized, bursty radiation observed at Toyokawa at 1 and 2 GHz, indicated that an electron-cyclotron maser operated during the flare. We derive 360 to 660 gauss as the maximum field strength in flaring loops.

This paper was presented at the U.S.-Japan Seminar "Recent Advances in the Understanding of Solar Flares," October 5-8, 1982, Tokyo, Japan.
Sol. Phys. 86, 451 (1983).

TWO FREQUENCY IMAGING OF MICROWAVE IMPULSIVE FLARES NEAR THE LIMB

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ABSTRACT

Using the VLA, we observed two impulsive microwave and hard X-ray flares that occurred close to the solar limb on 1981 Nov. 21 and 22. Images were obtained simultaneously at 4.9 and 15 GHz every 10 s during the ≈5 min duration of the flares. Even though the radio and hard X-ray time histories indicated that they were simple impulsive flares, the VLA observed no 4.9 GHz radiation at all from one flare, and from the other, the 15 GHz radiation emanated from a smaller and lower source and a different location than did the 4.9 GHz radiation. In the latter flare, the degree and sense of circular polarization was also different in the two sources, and both showed complex variations with time.

We interpret the observations in terms of an inhomogeneous flare volume with the magnetic field strength and orientation varying with position, both transverse to and along the line of sight. The 4.9 GHz radiation of the 22 Nov. flare probably arose mainly from thermal electrons with $T \sim 10^7$ K.

The 15 GHz radiation of the two flares probably arose from electrons of $E \sim 300$ keV in a weak, nonthermal tail. The derived field strength and heights of the two sources were ≈300 G and <3000 km respectively. Because both the thermal bremsstrahlung and gyrosynchrotron radiation mechanisms emit (and absorb) low frequency radiation more strongly than high, we conclude that the 4.9 GHz radiation was preferentially absorbed somewhere along the path from flare to Earth. The Hα pictures show that the radiation passed directly over a large sunspot, and we suggest that gyroresonance absorption at the 3rd harmonic ($B \approx 600$ gauss) removed the 4.9 GHz radiation; however, absorption at the 9th harmonic, being far smaller, did not significantly affect the 15 GHz radiation.

Subject headings: Sun: flares--Sun: radio radiation--Sun: hard X-rays

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To be submitted to The Astrophysical Journal (1985)

THE ASTROPHYSICAL JOURNAL, 259:L41–L45, 1982 August 1

RADIO WAVE HEATING OF THE CORONA AND ELECTRON PRECIPITATION DURING FLARES

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Received 1982 March 1; accepted 1982 April 23

ABSTRACT

Electron-cyclotron masers, excited while energy release is occurring in a flaring magnetic loop, are likely to generate extremely intense radiation at decimeter wavelengths. The energy in the radiation can be comparable with that in the electrons associated with hard X-ray bursts, i.e., a significant fraction of the total energy in the flare. Essentially all of the radio energy is likely to be reabsorbed by gyroresonance absorption, either near the emitting region or at some distance away in neighboring loops. Enhanced diffusion of fast electrons caused by the maser can lead to precipitation at the maximum possible rate, and hence account for hard X-ray emission from the footpoints of the magnetic loops.

Subject headings: magnetic fields — masers — radiation mechanisms — stars: radio radiation — Sun: radio radiation

THE ASTROPHYSICAL JOURNAL, 259:844-858, 1982 August 15

ELECTRON-CYCLOTRON MASERS AS THE SOURCE OF CERTAIN SOLAR AND STELLAR RADIO BURSTS

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Received 1981 October 8; accepted 1982 March 4

ABSTRACT

High brightness temperatures ($\gtrsim 10^{10}$ K) and high degrees of circular polarization in solar microwave spike bursts and in radio bursts from some stars can be explained in terms of an electron-cyclotron maser. A theory is developed for maser emission due to energetic electrons with a relatively mild loss cone anisotropy.

Wave growth is extremely fast, and the maser saturates quickly due to diffusion of electrons into the loss cone by the maser radiation itself. Amplification is due to electrons which have been accelerated or heated high in a magnetic flux tube (such as the top of a magnetic loop), some of which are lost by collisions at the bottom of the flux tube to form a loss cone, and others of which are reflected and drive the instability. Maser action is fastest at the fundamental of the gyrofrequency, perhaps in the *O*-mode because *X*-mode emission may be suppressed by the plasma, but neither mode can, in general, escape through the second harmonic gyromagnetic absorption layer. Amplification of the second harmonic is sufficiently fast to account for the observations, and under plausible conditions, this radiation can escape with a brightness temperature of 10^{16} to 10^{17} K. Individual bursts of maser emission are confined to a narrow frequency range and to a thin cone at a large angle (70° to 85°) to the magnetic field.

Subject headings: masers — stars: radio radiation — Sun: radio radiation

Adv. Space Res. Vol.2, No.11, p.185, 1983
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0273-1177/83/110185-0153.00/0

ON THE EFFECTS OF ELECTRON-CYCLOTRON MASERS DURING FLARES

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EXTENDED ABSTRACT

First recognized by Wu and Lee (Ap. J. 230, 621, 1979), electron-cyclotron masers can be activated under very mild conditions. Large growth rates can occur even for relatively mild anisotropies in the electron velocity distribution, e.g., the one-sided loss cones that commonly occur when electrons with small pitch angles precipitate into high density regions at the footpoints of flaring loops while others are reflected in the converging field in the corona. Maser action can plausibly occur at the second harmonic of the local gyrofrequency and so explain certain very bright ($\gtrsim 10^{10}$ K) microwave bursts from the sun and other stars. However, the preponderance of the energy is at the first harmonic.

We suggest that masers operating at the local gyrofrequency in a flaring loop generate radiation at decimeter wavelengths that is a significant fraction of the total energy of the flare, in fact (and not coincidentally) comparable with the energy in electrons associated with hard X-ray bursts. Essentially all of the radio energy is trapped in the corona and serves to produce localized heating in a volume large compared with the energy release region. Thus it can transfer energy by radiation from one magnetic loop to another, possibly inducing further instabilities, and spreading the course of the flare. Eventually the energy probably escapes the corona as soft X-rays. The electron-cyclotron maser saturates by extracting the perpendicular energy of the electrons, thereby diffusing them into the loss cone at the maximum possible rate; the enhanced precipitation into the footpoints can produce bright emission in hard X-rays, EUV and Hα and remove any necessity for directive acceleration in the energy release region.

Details of the proposed mechanism and effects are contained in two papers by Melrose and Dulk (Ap. J. 259, 1982).

This work was sponsored by NASA under grants NAGW-91 and NSG-7287 to the University of Colorado.

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THE ASTROPHYSICAL JOURNAL, 282:000–000, 1984 July 1

RADIO-FREQUENCY HEATING OF THE CORONAL PLASMA DURING FLARES

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Received 1983 October 19; accepted 1984 January 5

ABSTRACT

We develop a model for the radio-frequency (RF) heating of soft X-ray emitting plasma in solar flares due to absorption of amplified cyclotron radiation. The radiation, carrying $\sim 10^{27}$ to $\sim 10^{30}$ ergs s^{-1}, is generated through maser emission following partial precipitation of electrons in one or more flaring loops. The maser operates in a large number of small regions, each producing an "elementary burst" (EB) of short duration. This radiation propagates either directly or after reflection to the second-harmonic absorption layer, where it is absorbed by thermal electrons. The properties of EBs and the heating of the electrons in the absorption layer are discussed in detail. RF heating and evaporation models for the production of soft X-ray emitting plasma are compared. Properties of the RF heating model that explain observed features are energy transport across field lines, rapid heating (in ~ 1 s) of coronal plasma to $\approx 3 \times 10^7$ K, and instigation of turbulent velocities up to the ion sound speed.

Subject headings: radiation mechanisms — Sun: corona — Sun: flares — Sun: radio radiation

THE ASTROPHYSICAL JOURNAL, 273:249-254, 1983 October 1

RADIO EMISSION FROM AM HERCULIS: THE QUIESCENT COMPONENT AND AN OUTBURST

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Received 1983 February 7; accepted 1983 March 14

ABSTRACT

The Very Large Array (VLA) was used to search for radio emission from AM Herculis type binaries. The recent detection of 4.9 GHz radio emission from AM Her was verified, and upper limits for the flux density at 1.4 and 15 GHz were obtained. Upper limits of about 0.2 mJy (3 σ) for the 4.9 GHz radiation from VV Pup, EF Eri, PG 1550+191, CW 1103+254, and AN UMa were also obtained, although for AN UMa, a 0.3 mJy source was detected nearby.

A remarkable outburst of radiation from AM Her at 4.9 GHz was also detected. The outburst lasted about 10 minutes, was ~20 times more intense than the quiescent emission, and was essentially 100% circularly polarized.

It is suggested that electrons with energies of ~500 keV trapped in the magnetosphere of the white dwarf can account for the quiescent emission of AM Her, provided that the electron energy spectrum is quite hard and that the spectral hardness or number density of energetic electrons increases with radius. The outburst is probably due to an electron-cyclotron maser which operates near the surface of the red-dwarf companion. Plasma radiation is a less likely mechanism but cannot be ruled out. The implied existence of a localized magnetic field of ~1000 gauss and a corona on the red dwarf has important consequences for the mass transfer properties, field line interactions, and the variable activity.

Subject headings: radiation mechanisms — stars: binaries — stars: individual — stars: magnetic — stars: radio radiation

I. INTRODUCTION

Cataclysmic variables are close binary systems containing a white dwarf which accretes matter from a lower main-sequence companion star. The AM Herculis binaries, a subclass of cataclysmic variables, have a number of remarkable properties and are characterized by the strong linearly and circularly polarized light they emit (Tapia 1977; Chiappetti, Tanzi, and Treves 1980). Zeeman spectroscopy has revealed magnetic fields of $\sim 2 \times 10^7$ gauss in AM Her (Schmidt, Stockman, and Margon 1981) and CW 1103+254 (Stockman *et al.* 1982), while the presence of several cyclotron lines in the optical spectrum of VV Puppis indicates a magnetic field of 3×10^7 gauss (Visvanathan and Wickramasinghe 1979). The magnetic fields of the remaining half-dozen AM Her binaries have not yet been directly determined. However, theoretical models for the optical polarization observed in all of these systems suggest that it arises as a result of cyclotron emission at harmonic numbers $s \approx 5$-15. If $f_B = eB/2\pi mc$ is the cyclotron frequency in the emitting region, which is believed to be close to the white dwarf, the magnetic field of the white dwarf, B, is a few times 10^7 gauss in all of these systems (Chanmugam and Dulk 1981; Meggitt and Wickramasinghe 1982). The magnetic field of the white dwarf is sufficiently strong that its magnetosphere encompasses the companion star. Hence, unlike other cataclysmic variables, no accretion disk is formed. Instead, the accreting matter is channeled along an accretion column onto the magnetic pole(s) of the white dwarf (Chanmugam and Wagner 1978). A strong shock is formed near the surface of the white dwarf where the matter is heated to temperatures $T \approx 10^8$ K ($kT \approx 10$ keV) and produces hard X-rays (Rothschild *et al.* 1981). Below the shock the polar cap is heated by the hard X-rays to $T \sim 10^5$ K ($kT \sim 10$ eV), giving rise to soft X-ray and UV emission (Raymond *et al.* 1979). The optical, X-ray, and UV emission vary with the binary period (~1-3 hr), with no shorter periodic time variations present, indicating synchronous rotation.

Recently, radio emission from AM Her at 4.9 GHz ($\lambda \approx 6$ cm) was discovered with the VLA[1] by Chanmugam and Dulk (1982, hereafter CD82). In this paper we report on new observations of AM Her which confirm the detection at 4.9 GHz and give upper limits to the flux density at 1.4 and 15 GHz. In addition, we report the discovery of a remarkable outburst at 4.9 GHz, in which

[1] The National Radio Astronomy Observatory Very Large Array is operated by Associated Universities, Inc., under contract with the National Science Foundation.

Astron. Astrophys. 124, 103–107 (1983)

ASTRONOMY AND ASTROPHYSICS

The Sun at 1.4 GHz: intensity and polarization

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Received December 21, 1982; accepted March 14, 1983

Summary. We present 1.4 GHz radio pictures of the Sun made on 1981 September 26 using the VLA[1] with a resolution of 40″. Features observed include active regions, limb brightening, coronal holes and filament channels: all correspond well with features seen in Hα or He λ10830 Å, and can be explained as relative enhancements or depressions of free-free bremsstrahlung from the corona and upper transition region.

The degree of circular polarization of the radiation from active regions ranges up to 0.2 and the sense corresponds, with a few exceptions, with the polarity of the photospheric magnetograms, even though the 1.4 GHz radiation arises from the corona at a height of ~10 to ~50 Mm. The polarization is in the sense of the x-mode and is highest near the edges of active regions, whereas the brightness is highest (maximum of 2.2 10^6 K) near the line of zero polarization. The polarization can be explained by the different effects of the magnetic field on the bremsstrahlung opacities of the two modes; the observed values imply field strengths between about 20 and 70 Gauss near the boundaries of the active region corona.

Key words: Sun: radio radiation – Sun: magnetic fields – Sun: active regions – Sun: coronal holes

1. Introduction

For several decades the Sun has been observed at frequencies near 1.4 GHz (λ ≈ 20 cm) with a resolution that has steadily improved. Observations at this frequency are particularly interesting because the radiation arises from both the transition region and corona, with the coronal contribution being dominant in active regions where the coronal density is higher than average, substantial in typical quiet regions of average density, and nearly absent in low density regions such as coronal holes. Two dimensional observations with ≈3′ resolution were made regularly at Fleurs, Australia (Christiansen et al., 1957). From these and related observations, limited information was derived on the structure of the quiet solar atmosphere, but significant progress was made toward understanding the "slowly varying component", i.e. the enhanced radiation from the corona above active regions (e.g. review by Christiansen, 1966). By 1966 it was generally agreed that the majority of the radio emission from active regions is due to thermal bremsstrahlung from hot (1 to 3 10^6 K), high density electrons (Newkirk, 1961) although, at frequencies from about 5 to 15 GHz, gyroresonance emission also plays a role (Zheleznyakov, 1962; Kakinuma and Swarup, 1962).

Considerably better angular resolution was achieved in the mid to late 1970s with the construction of the Westerbork Synthesis Radio Telescope (WSRT) and the Very Large Array (VLA). WSRT observations at 1.4 GHz with 20″ by 61″ resolution (Chiuderi Drago et al., 1977) showed that various parts of bright (brightness temperature $T_B > 10^6$ K) active regions can be polarized to ≈5% while the overall polarization (e.g. with a 3′ beam) is nearly zero; however, portions of dim ($T_B < 10^6$ K) decaying active regions can be polarized to ≈25%. At higher frequencies, above about 3 GHz, there are two components: a broad distribution of low brightness ($T_B < 0.5\ 10^6$ K), and moderate polarization (<20%) which is cospatial with the underlying plage, and one or more cores (size <10″) of high brightness ($T_B > 10^6$ K), and high polarization (>50%) (e.g. Pallavacini et al., 1979; Alissandrakis et al., 1980; Felli et al., 1981). It is now believed that the broad component results from free-free bremsstrahlung and the small cores from gyroresonance emission at approximately the 3rd harmonic of the gyrofrequency in fields up to 1000 Gauss; these cores – and high fields – are located in the corona, usually, but not always, close to sunspots (e.g. review by Marsh and Hurford, 1982).

The characteristics of the quiet Sun, away from active regions, are not very well known at frequencies below ≈5 GHz. It was relatively recently that Dulk et al. (1977) found that coronal holes can be seen on the Fleurs maps at 1.4 GHz whenever solar activity is low enough to reduce confusion. In their study of one hole, Dulk et al. compared radio and EUV brightnesses and concluded that none of the then existing models of the transition region and corona could explain both. On the other hand, Chiuderi Drago and Poletto (1977) argue that the problem exists only for the corona. A similar situation may exist for quiet regions as well as coronal holes. So far as we know, this discrepancy has not yet been explained.

In this paper we present new observations of the 1.4 GHz Sun, its intensity and polarization, made with the VLA on 1981 September 26. We then compare the 1.4 GHz observations with near-simultaneous observations in He λ10830 Å and magnetograms from Kitt Peak National Observatory.

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1 The Very Large Array of the National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation

Maps of Centaurus A from Molonglo and Culgoora

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Introduction

While Centaurus A (NGC 5128) is not a particularly powerful radio galaxy, its proximity (~5 Mpc) permits us to obtain linear resolution an order of magnitude better than can be obtained for the more powerful, distant radio galaxies. Thus one can hope to make meaningful comparisons between the morphologies seen over the electromagnetic spectrum from γ-rays to metre waves. This should lead to a more complete understanding of the energy production mechanisms and evolutionary histories of these objects.

Maps of Cen A have been made over the last 30 years with a variety of radio telescopes at frequencies ranging from 19.7 MHz to 10.7 GHz. The earlier low-resolution maps by Shain (1958) at 19.7 MHz, Sheridan (1958) at 85.5 MHz and Cooper *et al.* (1965) at 406, 960, 1410 and 2650 MHz were able to trace emission over an angular area ~8°×4° centred on the peculiar elliptical galaxy NGC 5128. Later maps with an order-of-magnitude improvement in angular resolution, by Lockhart and Sheridan (1970) at 80 MHz, Slee and Sheridan (1975) at 160 MHz, Cameron (1969, 1971) at 408 MHz, Schwarz *et al.* (1974) at 1410 MHz, Christiansen *et al.* (1977) at 1415 MHz, Little (1961) at 3.3 GHz, Gardner and Whiteoak (1971) at 5 GHz and Price and Stull (1973) at 10.7 GHz, were not able to detect the emission from the low-surface-brightness outer lobes but did succeed in properly resolving the inner north-east and south-west lobes. Polarization studies by Bracewell *et al.* (1962), Cooper *et al.* (1965), Gardner and Whiteoak (1971), Price and Stull (1973) and Schwarz *et al.* (1974) showed that ordered linear polarization was present over most of the large area occupied by the source; in the inner lobes the linear polarization reached levels of ~60% in some areas at 10.7 GHz. A recent map from the VLA at 1420 MHz (Schreier et al. 1981), with angular resolution 31"×10" arc, shows the presence of three central sources, one of which is believed to be coincident with the nuclear engine at the centre of the optical galaxy, the other two sources being coincident with condensations in the X-ray jet (Feigelson *et al.* 1981) which extends from the nucleus towards the inner north-east radio lobe. This map is also notable for confirming the presence of considerable structure in the inner radio lobes, a feature which was first seen in the 1415 MHz map of Christiansen *et al.* (1977).

In this paper we present maps of comparable angular resolution (~50" arc) from Culgoora at 327 MHz and from Molonglo at 843 MHz. These maps contain information on the central sources first detected by Christiansen *et al.* (1977) and Schreier *et al.* (1981) at 1420 MHz. They show that the structure in the inner radio lobes in constant over at least a 4.4/1 frequency range.

Proc. Astron. Soc. Australia, 5, 247-251 (1983).

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. A12, PAGES 10,065-10,071, DECEMBER 1, 1983

CYCLOTRON MASER EMISSION OF AURORAL Z MODE RADIATION

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Abstract. Z mode radiation has been observed in the auroral zones where the plasma frequency ω_p is less than the electron cyclotron frequency Ω_e. We explore the possibility that this radiation is generated in the same way as the X mode radiation of the auroral kilometric radiation (AKR), i.e., by cyclotron maser emission driven by a loss cone distribution, specifically by electrons reflected at a lower height and propagating upward. We calculate the growth rate for the Z mode by using a method developed for the X mode and the O mode. We find: (1) Growth occurs in a small crescent-shaped region of $\omega - \theta$ space just outside a forbidden zone near $\theta = 90°$ with ω between Ω_e and the upper hybrid frequency. (2) The temporal growth rate for the Z mode is less than that for the (unsuppressed) X mode but comparable with that of the O mode; for $\omega_p/\Omega_e > 0.3$ the X mode is suppressed and the growth of the Z mode and the O mode compete for the available free energy. Because of the low group speed of the Z mode its spatial growth rate is higher than that of the O mode, giving it an advantage. (3) The product of the spatial growth rate and the bandwidth of the growing waves for the Z mode is comparable with that for the (unsuppressed) X mode and is much greater than that of the O mode. (4) Although all growing Z mode waves have slightly upward directed wave normals ($\theta > 90°$), most have downward directed rays, many at angles θ_g between 50° and 70°, and so can propagate toward regions where $\omega < \Omega_e$. We argue that these properties suggest that loss cone driven cyclotron emission may be the mechanism generating the observed auroral Z mode radiation.

1. Introduction

Broadband Z mode radiation has been detected in auroral cavities where the plasma frequency ω_p is appreciably less than the electron cyclotron frequency Ω_e. Calvert [1981] reported observations with the Hawkeye satellite, Benson [1982] with the ISIS 1 topside sounder and Gurnett et al. [1983] with the polar orbitting DE-1 spacecraft. It seems that Z mode radiation is a common feature of the auroral zones and that it had not been identified earlier because it is difficult to distinguish from auroral hiss under conditions when $\Omega_e > \omega_p$. The frequency band in which the Z mode can exist overlaps with the upper end of the whistler band and hence of auroral hiss. There is not a strong correlation between the observed Z mode radiation and either auroral hiss or auroral kilometric radiation (AKR), although the correlation is somewhat better with hiss. The intensity of the Z mode radiation is about 10^{-3} of that of the simultaneously detected AKR [Gurnett et al., 1983].

By analogy either to the generation of hiss or to the generation of AKR there are two obvious possibilities for the generation of Z mode radiation. Hiss is thought to be generated through amplified Cerenkov emission by downgoing electrons [Swift and Kan, 1975; Maggs, 1976; Yamamoto, 1979; Melrose and White, 1980; Lotko and Maggs, 1981]. Cerenkov emission requires a large refractive index, and the Z mode has a resonance (i.e., an infinite refractive index) at $\omega = \omega_+(\theta)$ with $\omega_+(\theta) > \Omega_e$ for $\Omega_e > \omega_p$. The observed Z mode radiation would then be attributed to downward propagating radiation initially generated at $\omega > \Omega_e$. Gurnett et al. [1983] have commented briefly on this mechanism. Here we discuss the other, a mechanism analogous to that for AKR.

Following the suggestion by Wu and Lee [1979] it is now widely accepted that AKR is generated through a loss cone driven cyclotron maser emission by reflected upgoing electrons [Omidi and Gurnett, 1982; Melrose et al., 1982; Wu et al., 1982; Dusenbery and Lyons, 1982]. Hewitt et al. [1982] explored the properties of this maser, including emission in both magnetoionic modes above their cutoff frequencies at harmonics $s = 1$, 2, and 3. They performed detailed numerical calculations for an idealized but fairly realistic loss cone distribution function, and developed a semiquantitative theory including all these effects. The properties of the waves were assumed to be determined by magnetoionic theory, i.e., the dispersion is due solely to a relatively dense cold background plasma.

More recently, Hewitt and Melrose [1983] extended the analysis to include emission near the cutoff frequencies. In the present paper we report a further extension to include cyclotron maser emission in the Z mode. We find that the Z mode can grow in a narrow, crescent-shaped band in $\omega - \theta$ space (θ is the wave normal angle

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Paper number 3A1483.
0148-0227/83/003A-1483$05.00

Electron Cyclotron Masers during Solar Flares

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1. Introduction

It has been suggested (Holman *et al* 1980; Melrose and Dulk 1982a) that solar microwave spike bursts are due to electron cyclotron maser action. These bursts have been observed in the range 1-3 Ghz, and occur in conjunction with flare-associated impulsive microwave and hard X-ray bursts. The bursts have rise times of a millisecond or less (e.g. Slottje 1978). Their high brightness temperatures, exceeding 10^{11} K, and high degrees of circular polarization ($\simeq 100\%$) favour a coherent emission mechanism such as cyclotron maser emission. Melrose and Dulk (1982b) suggested that a large fraction of the energy in the flare can be radiated through cyclotron maser emission as the fundamental. Such radiation does not escape the Sun, but is reabsorbed at the second harmonic of the cyclotron frequency. This leads to radiofrequency heating of regions around, but removed from, the flare site. In order to investigate the radiofrequency heating it is important to determine how the maser emission turns on and where it originates in relation to the flare itself. It is our purpose in this paper to explore a simple model for the dynamics of the electrons which produce the maser emission and to use the model to investigate the conditions under which the maser turns on. In section 2 we discuss the magnetic field in the flaring region in terms of a parabolic model, and solve for the motion of a particle in this model. In section 3 we discuss the two simple limiting cases of impulsive and continuous injection of energetic particles, and discuss the evolution of the distribution functions in each case. In section 4 we describe the theory of cyclotron maser action and show how it applies to the models, and in section 5 we discuss the implications of our results.

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2. Particle Dynamics in a Magnetic Flux Tube

We assume that the particles responsible for the microwave spike bursts are energetic electrons in a coronal magnetic flux tube shaped like an arch, its two footpoints embedded in the dense solar atmosphere. It is commonly thought that solar flares occur when twisted field lines in such arches suddenly reconnect and relax, releasing large amounts of energy. Some of this energy heats the ambient plasma, producing the required energetic electrons. We assume that the magnetic field is minimum at the top of the arch and increasing towards the footpoints. We suppose that the creation of energetic particles occurs at the top of the arch, although the model may easily be changed to accommodate another release site. The electrons travel down the flux tube and either mirror at a certain height above the atmosphere, or precipitate into the dense chromospheric plasma and thermalize, producing the observed hard X-ray bursts.

Let s denote the distance along a field line from the top of the arch; s is positive for one leg and negative for the other. We suppose that the magnetic field varies with distance along a field line according to a parabolic law

$$B(s) = B_0(1+s^2/d^2) \qquad (1)$$

where d is a scale length for changes in the magnetic field and B_0 is the field at the top of the arch. A recent study showed two examples of Hα loops in active regions which were well-fitted by a dipole model (Chen Chuan-Le and Loughhead 1983) and (1) is a reasonable approximation to this. We ignore the curvature of the loop, assuming its effects to be negligible as long as the radius of curvature is much larger than the gyro radius. Any twisting of the field lines is seen by the particles as merely increasing the distance over which the field changes, i.e., an increase in d.

Neglecting scattering, the motion of particles in the flux tube is described by

$$m\frac{d\mathbf{v}}{dt} = q/c\ \mathbf{v}\times\mathbf{B} \qquad (2)$$

which reduces with the above assumptions (e.g. see Northrop, 1963) to

$$|\mathbf{v}| = \text{constant}, \qquad (3)$$

$$\sin^2\alpha/B(s) = \text{constant}, \qquad (4)$$

and

$$\frac{d^2s}{dt^2} = -v^2\sin^2\alpha_0/2\Omega_0 \cdot \frac{d\Omega}{ds}(s) \qquad (5)$$

where α is the pitch angle of the particle, i.e. the angle between $\mathbf{B}$ and the velocity $\mathbf{v}$, $\Omega(s) = qB(s)/mc$ is the gyrofrequency, and a subscript zero denotes the value of the quantity at $s = 0$. When we solve (5) with the magnetic field (1), to find

$$s(t) = d.\cot\alpha_0\sin(v(t-t_0)\sin\alpha_0/d). \qquad (6)$$

The time t_0 may be interpreted as the first time (after injection at $t = 0$) that the particle crosses the point $s = 0$. Rather than label an orbit with t_0 we may use instead the position of the particle at $t = 0$, s_0. In the next section we need to express s_0

CHAPTER 2

THE SOLAR ATMOSPHERE, SOLAR MAGNETISM AND SOLAR ACTIVITY

G.A. Dulk

The Sun is a normal star in the middle of its life. It is brighter and more massive than 90% of its neighbours. It is special to us - first, because it is the source of all forms of energy excepting nuclear, and second, because it is close enough to observe in detail, facilitating the study of some physical processes occurring on many stars. It is a relatively stable star with very small changes in its energy output even during the course of the gigantic explosions - the solar flares - which produce most of the radio radiation that is the subject of this book.

The purpose of this chapter is first: to give an introduction to the general structure of the solar atmosphere, especially the corona, which is the site of all of the metre-wave radio emissions; second, to outline the properties of active regions and flares that are most important to radio phenomena; and third, to describe solar magnetism, including the origin of the coronal magnetic field and its role in determining coronal structure and providing energy for flares and radio bursts. Entire books have been written on many solar topics: e.g., Gibson (1973) on the quiet Sun, Athay (1976) on the quiet chromosphere and corona, Svestka (1976) and Sturrock (1980) on solar flares, Zirker (1977) on coronal holes, Orrall (1981) on active regions, Kundu & Gergely (1980) on solar radiophysics, and Frazier (1982), who gives a semi-popular account of current research topics. In addition, an excellent series of reviews has appeared in the monograph edited by Jordan (1981), "The Sun as a Star".

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from Solar Radiophysics, D. J. McLean, ed., Cambridge Univ. Press, submitted.

CHAPTER 4. SOLAR FLARES

G.A. Dulk, D.J. McLean and G.J. Nelson

To set the stage for our study of metrewave radio bursts we summarize in this chapter the observed features of flares and their interpretation, and briefly review present theoretical ideas on the energy release process. We consider flares as they appear at various wavelengths from γ-rays to radio waves, and at various heights in the atmosphere from below the chromosphere through the corona and into interplanetary space.

Because flares include such wide-ranging phenomena it is not always easy to relate the manifestations in one wavelength or height range to those in another, and indeed the connections are often tenuous. Even within the radio domain the characteristics of metrewave and microwave radiation differ greatly because different emission mechanisms dominate in the two ranges and the sources are located in different regions. They are related because both are produced by high-energy electrons, but even so the acceleration mechanisms for the electrons may differ in the two cases. However, the flare is an entity, and it is important to understand the spatial and temporal relations among the phenomena observed in various regimes.

Here we describe flares in general, first giving an overall view and then describing the various manifestations more or less in order of increasing height, starting in the photosphere and proceeding to a height of 1 AU (the region of the Earth's orbit). At each height range, observations in specific wavelength bands have provided most information, although there is sometimes considerable overlap. Therefore we proceed from the white light flare through Hα, UV, EUV, γ-rays, hard X-rays, microwaves, soft X-rays, decimetre waves, metre and longer waves, and then to direct observations of shock waves and particles near 1 AU. General references on flares include the books by Svestka (1976) and Sturrock (1980). References which concentrate on particular topics are given in the appropriate sections.

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from Solar Radiophysics, D. J. McLean, ed., Cambridge Univ. Press, submitted.

CHAPTER 12. BURSTS OF TYPE III AND TYPE V

S. Suzuki and G.A. Dulk

12.1 INTRODUCTION

Type III bursts are probably the most intensively studied radio emission in all of astrophysics. Immense effort has gone into the elucidation of both the observational and theoretical aspects. The bursts have captured the attention of plasma theorists because a considerable body of information exists on the plasma parameters and because there is adequate space and time for the evolution of various particle and wave processes, uninterrupted by the presence of walls or boundaries. Even so, Type III bursts are not understood in detail; there are several crucial observational and theoretical aspects which have yet to be explained and reconciled.

In this chapter we describe the characteristics of Type III bursts and review the theories. We concentrate on the newer observations and theories, largely ignoring the historical development of the subject. We draw freely upon the many reviews of the subject: Wild et al. (1963); Kundu (1965); Zheleznyakov (1970); Wild & Smerd (1972); Stewart (1974a); Fainberg (1974); Space Science Reviews Special Issue (1974); Solar Radio Group Utrecht (1974); Fainberg & Stone (1974); Lin (1974); Smerd (1976); Rosenberg (1976); Melrose (1980a,b,c); Goldman (1983). In Chapter 11 of this book Grognard reviews one of the central problems of Type III burst theory, the propagation of electron beams through the corona and interplanetary space. In Chapter 8 Melrose discusses the other central problem, the conversion from Langmuir waves to electromagnetic waves.

from Solar Radiophysics, D. J. McLean, ed., Cambridge Univ. Press, submitted.

Astron. Astrophys. 134, 222–233 (1984)

ASTRONOMY AND ASTROPHYSICS

Type II bursts, shock waves, and coronal transients: The event of 1980 June 29, 0233 UT

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Received September 8, accepted December 2, 1983

Summary. Metric Type II bursts, due to shock waves in the solar corona, are known to be associated with flares and coronal transients. We give here the first description of an event observed jointly in visible light and spatially resolved radio, combining radioheliograph observations from Culgoora, Australia and visible-light observations from the SMM Coronagraph/Polarimeter (C/P). We find that the densities implied by the radio emission and deduced from the coronagraph data require the observed Type II burst sources, and hence the shock, to be located within the dense, ejecta material. A faint arc, visible in the C/P images, is situated well above both the transient loops and the Type II burst sources; it moves outward with a velocity of $\sim 900\,\mathrm{km\,s^{-1}}$, 50% faster than the loops. We suggest that this faint arc is due to compression of ambient material by another, earlier shock, without associated Type II radio emission. The observed density enhancement implies a compression ratio $1.3 < n_2/n_1 < 3$, and a corresponding Alfvén Mach number $1.2 < M_A < 3$. We further suggest that the outer shock is driven by the rising loops, but that the inner, Type II associated shock is due to a blast wave from the flare, which began several minutes after the start of the coronal transient. We also give estimates of the mass and energy of the entire transient event and find it to be somewhat smaller than the average ATM transient.

Key words: shock waves – the Sun: bursts, flares

1. Introduction

Metric Type II solar radio bursts, which are often associated with large solar flares, offer the chief evidence for shock waves occurring in the solar corona. Type II bursts were classified by Wild and McCready (1950) as a distinct type of burst on the basis of their appearance on a radio spectrograph. The bursts, which appear as narrow bands of emission that drift slowly to lower frequencies, were soon attributed to outward moving shocks that excite radio emission at the fundamental and second harmonic of the local plasma frequency. Perhaps the most direct evidence that Type II bursts are due to shock waves has been given by spacecraft observations (Malitson et al., 1973a, b; Boischot et al., 1980; Cane et al., 1982). These interplanetary bursts have many of the characteristics of metric Type II bursts, such as drift to lower frequencies (implying velocities around $1000\,\mathrm{km\,s^{-1}}$), intermittent brightening, and some indication (Cane et al., 1982) of fundamental-harmonic structure. Cane et al. (1982) have found that the Type II bursts observed with the ISEE-3 spacecraft are often (8 of 12 events) associated with interplanetary shocks observed with the same spacecraft, thereby firmly linking the two phenomena, although some shocks detected by the spacecraft have no associated Type II emission.

Coronal transients, great clouds of plasma ejected from the Sun, are inferred from OSO-7 and Skylab ATM coronagraph observations to occur as often as 1/d. These mass ejections obviously play an important role in the connection between flares and coronal shocks. It was found (Gosling et al., 1976) that 30% of the coronal transients observed with ATM were associated with Type II bursts and, conversely, almost all Type II bursts that occurred within 45° of the limb were accompanied by white-light transients. It was also found that transients associated with flares had higher speeds ($> 400\,\mathrm{km\,s^{-1}}$) than those without flares and that these faster transients were more likely to have associated Type II bursts.

The exact relationships among flares, shocks, and coronal transients is unknown, mainly due to the difficulty of coordinating radio, optical, and coronagraph observations. Despite the excellent white-light coronal observations provided by the HAO coronagraph on Skylab during 1973, no joint observations of a coronal transient and spatially resolved Type II burst were obtained during that mission. Stewart et al. (1974a, b) reported joint observations of two events with the Culgoora radioheliograph and the NRL coronagraph on the OSO-7 spacecraft. However, the radio observations extended to only about $2\,R_0$ while the inner field of view of the OSO-7 coronagraph was at $2.5\,R_0$, so no direct comparison of the two data sets was possible. From the timing of the transient and radio bursts they concluded that the Type II bursts for both events were located ahead of the transients' leading edges and thus indicated the existence of piston driven shocks. However, this conclusion was based on Type II heights derived from a rather high coronal density model (Newkirk's 1961) and not upon actual measurements of density in the Type II source regions. When the HAO Coronagraph/Polarimeter instrument (MacQueen et al., 1980) went into operation aboard the NASA Solar Maximum Mission (SMM) satellite, efforts were made to coordinate satellite and ground based observations of energetic solar events as part of the Solar Maximum Year. Because of these efforts, joint observations of coronal transients and spatially resolved radio bursts were obtained for a number of events; four of these included a Type II burst.

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* The National Center for Atmospheric Research is sponsored by the National Science Foundation

9.4 IMAGE RESTORATION TECHNIQUES - HOW GOOD ARE THEY?

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1 INTRODUCTION

Maps of the radio sky made with synthesis telescopes are imperfect. The most prominent defects usually arise from incomplete sampling of the complex visibilities by the antenna array. In regular arrays, aliased responses (grating rings) from sources which may or may not be in the mapped area are generally present. If the map-making procedure involves sampling of the visibility data on to a regular grid and transform by the fast Fourier transform (FFT) algorithm, then further aliasing is introduced. Receiving systems contribute noise to a map and, to a greater or lesser extent, introduce gain and phase errors. Fluctuations in the atmosphere and ionosphere also contribute to phase errors in the measured visibilities. Finally, antenna pointing errors and, in altitude-azimuth mounted antennas, beam non-circularities result in modulation of the detected signal and hence errors in the map.

Great ingenuity has been shown by astronomers and others in devising methods to remove these defects from maps, leaving behind an image of the 'true' sky, albeit convolved with some smoothing function. Image restoration procedures such as CLEAN (Högbom 1974; Schwarz 1978) and the maximum entropy method (MEM) (e.g. Gull & Daniell 1978) reduce the effects of incomplete sampling of visibilities and aliased responses in regular arrays and are commonly used. Aliased responses resulting from the FFT can be largely eliminated by use of suitable convolving functions in the visibility plane (e.g. Schwab 1978, 1983). Self-calibration techniques (e.g. Cornwell & Wilkinson 1981, 1983) can be used to remove antenna-based complex gain errors - e.g. errors contributed by the atmosphere or the receiver system.

In this paper we have the limited objective of exploring how well image-restoration techniques reproduce the actual sky brightness distribution from observations made with an incomplete array in the presence of random receiver noise. Gain errors are assumed to be zero and self-calibration techniques are not considered. We use an array simulation program developed as part of the Australia Telescope design studies. Three image restoration techniques are considered: CLEAN, MEM and a process we call the constrained positivity method (CPM). This last method was originally suggested by Högbom (1974), but as far as we are aware it has not been widely used, although variants have been employed in reconstructing limited phase data (e.g. Fienup 1978; Rogers 1980).

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Indirect Imaging, ed. J. A. Roberts, (Cambridge: Cambridge University Press), pp. 355-361.

RADIO WAVE HEATING IN IMPULSIVE FLARES, SHOCK WAVES, AND CORONAL MASS EJECTIONS

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ABSTRACT

Electron-cyclotron masers, excited while energy release is occurring in flaring magnetic loops, are likely to generate extremely intense radiation at decimetric wavelengths that will heat a large volume of coronal material very rapidly. This is likely to initiate a shock wave and type II bursts. However, it seems that at least in some flares, the beginning of coronal transient motion precedes the impulsive flare, and the ejecta probably represent more energy (in the form of moving material and ejected magnetic fields) than is in the low coronal flare. This suggests that the energy sources for the two phenomena are different.

STIP Symposium on Solar/Interplanetary Intervals, Eds. M.A. Shea, D. F. Smart and S. M. P. McKenna-Lawlor, (Chelsea, MI: Book Crafters Inc.), pp. 331-336.

Astron. Astrophys. 130, 39–45 (1984)

ASTRONOMY AND ASTROPHYSICS

Solar noise storms: the polarization of storm Type III and related bursts

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Received July 5, accepted August 23, 1983

Summary. We report the spectral and polarization characteristics of 19 noise storms that occurred during 1976–1982. All components of the storms – Type I bursts and continuum, storm Type III bursts, and fine structures such as reverse drift pairs – are found to have the same sense of circular polarization. While the degree of polarization p of Type I bursts and continuum is generally $p \gtrsim 0.5$, that of storm Type III bursts is almost always $p < 0.5$. Two sets of storm Type III bursts stand out: one with $p \lesssim 0.2$ and another with $p \gtrsim 0.3$. Because these sets respectively have degrees of polarization so similar to those of fundamental (F) the harmonic (H) components of non-storm $F-H$ pairs, we deduce that storm Type III bursts are due sometimes to fundamental plasma radiation and sometimes to harmonic. However, $F-H$ pairs are extremely rare among storm Type III bursts.

Key words: solar radio astronomy – polarization – noise storms – Type III bursts – Type I bursts – reverse drift pairs

I. Introduction

At metre and decametre wavelengths it is common to observe long-lasting "storms" of radio emission. At metre wavelengths the storms typically consist of myriads of Type I bursts which in the stronger storms are superimposed on a continuum (e.g. McCready et al., 1947; Wild, 1950). At long metre and decametre wavelengths the storms typically consist of myriads of Type III bursts which also may be superimposed on a continuum (Wild, 1957; Warwick, 1965). Simultaneous with most Type III storms at decametre wavelengths there are Type I storms at metre wavelengths (Boischot et al., 1970). The Type III storm bursts usually start near the low frequency edge of the Type I storm (Malville, 1962), continue to the lowest frequencies observable from Earth (typically about 10 to 20 MHz) and are often observed by spacecraft at a few megahertz and lower (e.g. Fainberg and Stone, 1974). Various properties of Type III storms have been studied by the authors mentioned above and by Hanasz (1966), Warwick and Dulk (1969), de la Noë and Boischot (1972), Stewart and Labrum (1972), Moller-Pedersen (1974), Suzuki and Gary (1979) and Duncan (1981).

Since 1949 it has been known that Type I storms tend to be highly circularly polarized (Payne-Scott, 1949; Payne-Scott and Little, 1951). However, no systematic study of the polarization of storm Type III bursts seems to have been made.

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In this paper we report on the polarization of storm Type III bursts and its relation to that of the accompanying Type I storm. We also report the starting frequency of the storm Type III bursts, their character (i.e. whether of the usual, smooth variety or Type IIIb), and, if reverse drift pair bursts were present, their polarization. We report on 19 different storms and 70 d of observations during 1976 to 1982.

The motivation for our study is our desire to use the polarization data to establish whether storm Type III bursts are due to fundamental or harmonic radiation. Without this knowledge it is not possible to develop a proper theory for the bursts. At kilometre wavelengths the evidence implies that only one kind of burst is present, and it is generally believed to be the harmonic (e.g. Fainberg and Stone, 1974); this applies both to storm Type III and classical, isolated or grouped Type III bursts. If the bursts are indeed harmonics then there are severe problems in explaining time delays between radio burst onsets, arrival of electron streams at the spacecraft and the detection of Langmuir turbulence at the spacecraft (Lin et al., 1981); the question has even been raised as to whether generation of Langmuir waves and their subsequent conversion to electromagnetic waves is the radiation mechanism for the radio bursts (e.g. review by Goldman, 1983). On the other hand, if the bursts are fundamentals, then there are problems in explaining other properties of the bursts, one being the apparent envelopment of the spacecraft by the radiating source (disappearance of spin modulation) when the electron stream is only about half-way from the Sun.

In Sect. II we describe the equipment that we used in the present study and our selection criteria. In Sect. III we present our results, and in Sects. IV and V we discuss their interpretation in terms of the motivation listed above.

II. Observations

The data of this study were recorded at Culgoora with two instruments.

1. The dynamic spectrograph (Sheridan, 1967) operates over the frequency range 8 to 8000 MHz and records the intensity as a function of frequency and time on 70 mm film. In the frequency range of most interest for this study, 24 to 220 MHz, the spectrum is swept four times per second and separate recordings are made with high and low gain so that both strong and weak bursts can be recorded.

2. The spectropolarimeter (Suzuki and Sheridan, 1977) sweeps over the range 24 to 220 MHz twice each second and records the degree and sense of circular polarization on 16 mm colour film.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. A2, PAGES 897-904, FEBRUARY 1, 1984

ELECTRON-CYCLOTRON MASER EMISSION: RELATIVE GROWTH AND DAMPING RATES FOR DIFFERENT MODES AND HARMONICS

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Abstract. We calculate and compare the temporal growth rate and the number of e-folding growths for the following wave modes due to a loss-cone-driven cyclotron maser: fundamental x, o, and z modes and second harmonic x and o modes. The dominant mode of the maser should be the fastest growing mode for a saturated maser and should be the mode with the greatest number of e-folding growths for an unsaturated maser; this mode is the fundamental x mode for $\omega_p/\Omega_e < 0.3$, the z mode (or perhaps the fundamental o mode) for $0.3 < \omega_p/\Omega_e < 1.0$, and the z mode (or perhaps the second harmonic x mode) for $1.0 < \omega_p/\Omega_e < 1.3$. We discuss the effect of cyclotron damping by thermal electrons on the growth. Numerical calculations show that the effect is important only when the ratio of the mean energies of the thermal and maser emitting electrons exceeds 0.1-0.2. An analytic expression for the damping rate is derived and is used to show that some earlier treatments of cyclotron damping greatly overestimate the effect for loss-cone-driven maser emission. These results, when applied to AKR, imply that only either the fundamental x mode (for $\omega_p/\Omega_e < 0.3$) or the z mode (for $\omega_p/\Omega_e \gtrsim 0.3$) is produced directly by maser emission. We suggest (1) that an o mode component in AKR might be due to partial reflection of x mode radiation incident onto sharp overdense plasma intrusions of the kind observed in the auroral cavity and (2) that a second harmonic component can be produced by coalescence of two z mode waves.

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Paper number 3A1789.
0148-0227/84/003A-1789$05.00

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THE ASTROPHYSICAL JOURNAL, 282: 000–000, 1984 July 1

RADIO-FREQUENCY HEATING OF THE CORONAL PLASMA DURING FLARES

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Received 1983 October 19; accepted 1984 January 5

ABSTRACT

We develop a model for the radio-frequency (RF) heating of soft X-ray emitting plasma in solar flares due to absorption of amplified cyclotron radiation. The radiation, carrying $\sim 10^{27}$ to $\sim 10^{30}$ ergs s^{-1}, is generated through maser emission following partial precipitation of electrons in one or more flaring loops. The maser operates in a large number of small regions, each producing an "elementary burst" (EB) of short duration. This radiation propagates either directly or after reflection to the second-harmonic absorption layer, where it is absorbed by thermal electrons. The properties of EBs and the heating of the electrons in the absorption layer are discussed in detail. RF heating and evaporation models for the production of soft X-ray emitting plasma are compared. Properties of the RF heating model that explain observed features are energy transport across field lines, rapid heating (in ~ 1 s) of coronal plasma to $\approx 3 \times 10^7$ K, and instigation of turbulent velocities up to the ion sound speed.

Subject headings: radiation mechanisms — Sun: corona — Sun: flares — Sun: radio radiation

ACTIVITY AND MAGNETIC FIELDS ON STARS FROM RADIO OBSERVATIONS

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During the past few years, owing partly to the completion of the VLA, interest in radio observations of stars has had a resurgence. New instruments have provided an increase in sensitivity by an order of magnitude, accompanied by a considerably reduced risk of mistaking radio interference for stellar radiation. Gibson (1983) gives a summary of observations of the class of stars most extensively studied to date, i.e., flare stars of spectral type dMe. Here I will describe some of the newest results on several classes of stars and comment on their interpretation in terms of stellar activity and stellar magnetic fields. I will confine my attention to outbursts of radio radiation, omitting from consideration the quiescent or steady emission that comes from some stars such as RS CVn and AM Herculis type binaries, late type stars with coronae such as χ^1 Orionis; this aspect is discussed by Brown and Crane (1978), Gary and Linsky (1981), Topka and Marsh (1982) Chanmugam and Dulk (1982) and Gibson (1983).

Figure 1, from Gary, Linsky and Dulk (1982), shows an example of an outburst of radiation that has most of the characteristics of the five examples I will show on viewgraphs. The top frame, in which each data point represents a five minute integration, shows an approximately steady component of emission from UV Ceti which could be due to a hot, magnetically confined corona or to sustained, low level flaring activity. A drastic, short-lived increase in radiation is seen in the top panel in only one or two data points and in only one polarization. The burst is expanded in the lower panel, in which 10 s integrations were used, i.e., the shortest then available at the VLA. There are factor-of-two variations in flux from one 10 s interval to another, and the radiation is >80% circularly polarized. Careful measurements of source position revealed that the outburst arose not from UV Ceti itself but from its distant binary companion, also a dMe star.

Proc. Japan-France Seminar on Active Phenomena in the Outer Layers of the Sun and Stars, J.C. Pecker and Y. Uchida, eds., (Paris: Centre National de la Recherche Scientific), pp. 91-95 (1984).

TYPE III RADIO BURSTS IN THE INTERPLANETARY MEDIUM: THE ROLE OF PROPAGATION.

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SUMMARY. We analyze new observations of interplanetary Type III radio bursts in order to determine the role played by propagation effects between the true source and the observer. Some findings are: (1) large source altitudes, with the frequency of the radiation observed to come from a given height averaging 2 to 5 times the plasma frequency at that height, (2) increasing angular size of sources with angular distance from the Sun's center, (3) strong directivity of sources with the brightness temperature at $\lesssim$ 300 kHz being smaller for sources east of the Sun than west, and (4) excess propagation times of up to 500 s (1 AU of excess path length) or more when bursts are detected at two spacecraft. We also find that among 22 Type III bursts observed in association with Langmuir waves events at 1 AU, 20 occur in regions of average density, not in overdense regions as often has been suggested.

These observations provide strong evidence that propagation effects, group delays, ducting and/or scattering, greatly affect the observed heights, sizes and brightness temperatures of interplanetary Type III bursts, whether they are due to plasma radiation at the fundamental or harmonic, and also affect the arrival times of the radiation to a greater or lesser extent depending on the path from the source to the observer.

Astron. Astrophys., in press (1984).

TYPE III BURSTS IN INTERPLANETARY SPACE: FUNDAMENTAL OR HARMONIC?

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Received

SUMMARY. We study Type III bursts in the solar wind using observations of 120 relatively simple, intense and isolated bursts that were observed on the ISEE-3 spacecraft in the frequency range 30 to 1980 kHz. For many but not all bursts we identify several characteristics which indicate that the mode of emission changes from predominantly fundamental plasma radiation during the rise phase to predominantly second harmonic during the decay. In particular, there are a number of bursts whose trajectories encounter the spacecraft and fast electrons and Langmuir waves are observed. For these, and for radio frequencies near the local plasma frequency, the evidence is strong that radio emission is at the fundamental from burst onset until about the time of burst peak. Further, the fundamental emission begins in time coincidence with the start of the Langmuir waves. This finding should remove any doubt about the conventional belief that Langmuir waves are responsible for Type III bursts.

At kilometer wavelengths the characteristics of fundamental components compared with harmonics are (1) faster rise times, (2) higher brightness temperatures (sometimes in excess of 10^{14} K), (3) smaller source sizes, (4) a more pronounced east-west asymmetry of brightness temperature, (5) higher directivity and hence avoidance of locations near the limb, and (6) slightly differing directions of source centroids.

KEY WORDS: Type III bursts--radiation mode--plasma radiation--Langmuir waves

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Astron. Astrophys., in press (1984).

THE TYPE IV BURST OF 1980 JUNE 29, 0233 UT: HARMONIC PLASMA EMISSION?

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ABSTRACT

The coronal transient event of 1980 June 29, 0233 UT, was well observed by the HAO Coronagraph/Polarimeter aboard SMM and at meter radio wavelengths by the Culgoora Radioheliograph. The radio event consisted of a strong Type II (shock wave related) burst followed by weak Type IV (storm) continuum. We discuss the details of the Type IV portion of the event in terms of two possible emission mechanisms--plasma emission (at the second harmonic) and gyro-synchrotron emission. In support of the first alternative we find the following:

1) The 80 MHz Type IV source moves along the densest part of the transient in conjunction with the rising of the relevant (40 MHz) plasma level.

2) Both the 80 and 43 MHz sources are associated at all times with the coronal features whose inferred densities are high enough to account for the emission as harmonic plasma emission.

3) The polarization of the 80 MHz source is consistent with harmonic plasma emission.

4) At times, the spectrograph record shows weak Type III-like bursts that imply acceleration of electrons from the lower corona to energies of 1 to 3 keV.

We find that gyro-synchrotron emission is a possible mechanism only if more stringent requirements are met, viz., that the density of electrons of energy greater than 10 keV is about 10% of the ambient density, that the average energy is about 40 keV, and that the magnetic field strength at 2.5 solar radii is about 2.8 gauss. We conclude that this Type IV event is likely due to plasma emission at the 2nd harmonic of the plasma frequency.

Submitted to Astronomy and Astrophysics