Final Report for NASA Grant NAG5-7390

GENERATION AND SCATTERING OF RADIATION OBSERVED BY VOYAGER IN THE OUTER HELIOSPHERE

Period covered: 3/1/1998 - 2/28/2002

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i

1 Summary of Research Progress

Excellent progress was made under this grant on the generation and scattering of the 2-3 kHz radio emissions observed by the Voyager spacecraft in the outer heliosphere. These are the most powerful radio emissions produced in our solar system, surpassing even those of Jupiter and the Sun. The widely-held hypothesis pursued is that the radiation is generated near the electron plasma frequency f_p or near $2f_p$ as a shock wave traverses the heliosheath regions and/or heliopause predicted in the interaction region between the solar wind and the local interstellar medium. (Note that f_p^2 is proportional to the plasma density.) The traveling shock wave is plausibly associated with a global merged interaction region (GMIR). Accordingly, this so-called "GMIR model" is strongly analogous to the common interpretation of type II solar radio bursts and to radio emissions associated with Earth's bow shock, with coronal mass ejections (CMEs) and Earth's magnetosphere playing the role of a GMIR, respectively. Accordingly, Dr Cairns's work on type II bursts, Earth's foreshock, and stochastic growth theory (not described in detail here) strongly aided and complemented the research progress on the 2–3 kHz emissions described here.

Before concentrating on the science, a few words on the heritage of the grant are appropriate. It started with Dr Cairns as Principal Investigator (PI). When he moved to the University of Sydney (Australia) in July 1998, he became the grant's Co-Investigator but undertook to continue the research program with Professor Spangler as the PI. This arrangement has enabled excellent progress to be made, leveraging the investments of funds by both NASA and Australian sources. Collaboration with Professor G.P. Zank (UC Riverside; formerly of the Bartol Research Institute, University of Delaware) was a central element of the research program.

The 2–3 kHz emissions have occurred in two main episodes in 1983–84 and 1992–93, with several weaker events in between. The two main episodes occurred approximately 415 days after solar outbursts which subsequently engendered GMIRs moving past the Voyager and Pioneer spacecraft. Combining the propagation speeds with the timelags and other reasonable assumptions, Gurnett et al. [Science, 1993] inferred that the radiation started at distances of order 150 AU from the Sun, plausibly near the heliopause but well beyond the solar wind's termination shock. The radiation is composed of two components, one of which drifts upward in frequency (the so-called "transient emissions") while the other remains at a constant frequency (the so-called "2 kHz component"). Multiple questions required explanation at the start of the grant period, including: (i) Why and where does the observed radiation turn on? (ii) Why are no emissions observed at lower frequencies in the solar wind or from the inner heliosheath? (iii) Why is the radiation at frequencies $\approx f_p$ expected for the outer heliosheath? (iv) Where is the $2f_p$ radiation expected from type II burst and Earth's foreshock observations? (v) How does the radiation surmount the shock density ramp and propagate to the Voyager spacecraft? (vi) What explains the differences between the transient emissions and the 2 kHz component?

Six main contributions were made during the grant period, resulting in a detailed

semiquantitative theory for the radiation that answers questions (i) – (iv) in detail and question (v) qualitatively. These contributions are described in 9 papers published in the grant period and two more recent papers, and were presented in 13 talks (4 of them invited) at conferences and institutions. Lists of published papers and presentations are given in Sections 2 and 3, respectively.

First, we explicitly calculated how scattering of the radiation by density irregularities broadens the apparent angular extent of the source as a function of frequency [Cairns, 1998]. This effect increases dramatically as the plasma frequency f_p approaches the radiation frequency f, and so is very important for radiation generated near f_p or $2f_p$. Specifically, we generalized the two standard theoretical approaches (the parabolic wave equation analysis and geometric optics) to calculate the amount of angular broadening expected for arbitrary ratios $f/f_p \geq 1$, showed that both yield the same result, and argued that the results allowed one to interpret the variations with heliocentric distance of "roll modulatio" patterns in terms of the radiation source being at greater heliocentric distances than the Voyager spacecraft.

Second, we calculated the first theoretical dynamic spectra for the 2–3 kHz emissions by combining elements of the GMIR model (f_p and $2f_p$ emission upstream of a GMIR-driven shock) with Zank et al.'s [JGR, 1996] state-of-the-art simulation data for the 3-D density structure in the outer heliosphere [Cairns and Zank, 1999]. The results showed that a relatively intense emission with constant frequency, rather similar to the observed 2kHz component, can be expected from the emission in the outer heliosheath. However, no component similar to the transient emissions was observed, with the heliopause density ramp leading to drifting structures with far too short a timescale and with a frequency below rather than above the 2 kHz component, contrary to observations. One way to preserve the basic features of the GMIR model for the transient emissions is to postulate that other density structures with longer scale lengths exist in the outer heliosheath.

Third, a detailed, analytic theory was developed for why the radiation turns on beyond the heliopause, why it is primarily at likely values of f_p in the outer heliosheath, and why there is no emission in the solar wind and inner heliosheath. This theory [Cairns and Zank, 2001, 2002] predicts that the radiation turns on when the GMIR shock enters a region beyond the heliopause primed by an enhanced superthermal electron tail. The theory involves so-called "lower hybrid drive" (LHD), in which lower hybrid waves resonantly accelerate electrons into a superthermal tail, with the lower hybrid waves being produced by a ring-beam instability driven by pickup ions. The pickup ions result from charge-exchange of interstellar protons with so-called component 2 neutrals, which originated as shocked solar wind protons in inner heliosheath. Strong theoretical arguments predict that the ring-beam instability and LHD can only occur in the outer heliosheath region near (say 20 – 50 AU) the heliopause nose, near where the interstellar magnetic field is draped over the heliopause. Moreover, strong arguments based on known analytic theory for electron acceleration at the shock, the production of electron beams upstream of the shock, and the efficiencies of f_p and $2f_p$ radiation as functions of the beam parameters predict that

2

the intensity of f_p emission is greatly increased in the presence of the superthermal tail and dominates $2f_p$ emission. Qualitatively, then, this theory answers questions (i)–(iv) above.

Fourth, detailed qualitative ideas were advanced [Cairns and Zank, 2001, 2002] for how radiation produced upstream of the GMIR shock, at larger heliocentric distances, can reach the inner heliosphere, cf. issues (iv) and (v) above. The basic problem is that radiation produced at f_p and $2f_p$ upstream of the shock should be reflected at the shock's density ramp, where the local plasma frequency is approximately twice the upstream plasma frequency, thereby not being able to cross the shock. Our solution is to note that Zank et al.'s [JGR, 1996] simulations show that the plasma density (and so f_p) increases slightly with increasing heliocentric distance at the heliopause nose, but decreases slowly around the sides of the heliopause. Accordingly f_p radiation will be strongly scattered between the shock ramp and the upstream density gradient, diffusing slowly around the sides of the GMIR shock until it reaches locations where the shock is interior to the heliopause and so f_p is locally much smaller than the radiation frequency. At these locations the radiation will freely cross the shock and propagate into the inner heliosphere. In contrast, $2f_p$ radiation will be primarily lost into the local interstellar medium, since scattering is much weaker for it.

Fifth, reviews of the theory and observations of the 2–3 kHz emissions (and sometimes related phenomena) were prepared and published [Cairns et al., 2000; Cairns and Zank, 2001; Cairns and Kaiser, 2002]. Associated invited presentations were given at conferences.

Sixth, 3-D simulations of shock propagation through the outer solar wind to the heliopause and beyond were combined with observational data to predict whether and when the Bastille Day shock might produce a 2–3 kHz radio event [Zank et al., 2001]. While no radiation was observed above the Voyager background levels (even the 1993-84 and 1992-93 events were at most a factor of 3 above the background), two plausible explanations exist: (1) the GMIR shock was not sufficiently global, since it was not observed on all the Pioneer and Voyager spacecraft, for the shock to reach the region primed by Cairns and Zank's [2001, 2002] mechanism; (2) more recent work described below [Cairns et al., Adv. Space Res., in press, 2003] suggests that the radiation level depends sensitively on the shock speed and other parameters, so that perhaps the Bastille Day shock produced emissions below the Voyager thresholds.

Progress was also made on several minor projects not directly concerned with the 2–3 kHz radiation. First, Zank and Cairns [2000, 2001] developed a theory for low frequency (Alfvenic) waves driven by interstellar pickup ions in the solar wind. Based on stochastic growth theory (SGT), the theory predicts that the waves should be extremely bursty and difficult to detect using standard spectral techniques. Second, Mr Beau Bellamy, a student financed with Australian funds, worked with Dr Cairns and Dr C.W. Smith (University of Delaware) to determine observationally how the spectrum of density turbulence varies with heliocentric distance. A paper was submitted to JGR in July 2001. It is currently

awaiting revision and resubmission. Third, Dr Cairns worked with Dr R.R. Anderson (University of Iowa) to determine the observed flux densities of interplanetary type II solar radio bursts, for future comparisons with the new semiquantitative theory of Knock, Cairns et al. [JGR, 2001, 2003].

The last paragraph on science in this report describes the excellent progress made since Grant NAG5-7390 expired. In particular, we have combined the new theory for type II bursts [Knock et al., JGR, 2001, 2003] with the priming theory for turn-on of the 2–3 kHz radiation [Cairns and Zank, 2001, 2002] in order to make semiquantitative predictions of the levels, frequencies, and dynamic spectra of the 2–3 kHz radio emission. Specifically, Cairns et al. [Adv. Space Res., in press, 2003] predict semiquantitatively that the radiation should turn on once the GMIR shock enters the priming mechanism beyond the heliopause, f_p radiation should dominate $2f_p$ emission, and the radio fluxes should be of order those observed. Moreover, Mitchell, Cairns et al. [JGR, submitted, 2003] calculate dynamic spectra, using Zank et al.'s [JGR, 1996] simulations to give the 3-D plasma characteristics, finding that the simple GMIR model yields radiation with very similar frequency, time, and intensity characteristics to the observed 2-kHz component. These results are for a small source region, with a scale size of only ≈ 1 AU, whereas multiple such "ripples" should exist on the GMIR shock front, and do not include the low efficiency with which radiation is expected to propagate into the inner heliosphere [Cairns et al., Adv. Space Res., 2003]. The calculations also do not produce emissions analogous to the observed transient emissions. In conclusion, while great progress has been made and the current work is very exciting, further research is still required for us to develop a fully quantitative understanding of these emissions from the outer plasma boundaries of our solar system.

2   Publications Supported Directly by the Grant

1. Cairns, I.H., *Angular broadening for finite ratios of plasma frequency to radiation frequency*, **Astrophys. J.**, 506, 456, 1998.

2. Cairns, I.H., and G.P. Zank, First theoretical predictions for the dynamic spectra of the outer heliospheric radio emissions, **Geophys. Res. Lett.**, *26*, 2605, 1999.

3. Zank, G.P., and I.H. Cairns, *Pickup ion driven turbulence in the polar heliosphere: A stochastic growth model*, **Astrophys. J.**, 541, 489, 2000.

4. Cairns, I.H., P.A. Robinson, and G.P. Zank, *Progress on coronal, interplanetary, foreshock, and outer heliospheric radio emissions*, **Publ. Astron. Soc. Aust.**, 17(1), 22, 2000.

5. Cairns, I. H., and G. P. Zank, *Theories for radio emissions from the outer heliosphere*, in **"The Outer Heliosphere: The Next Frontiers"**, Eds K. Scherer, H.

Fichtner, H.-J. Fahr, and E. Marsch, COSPAR Colloq. Series Vol. 11, Pergamon (Holland), 253, 2001.

6. Zank, G. P., and I. H. Cairns, *Pickup ion turbulence: A stochastic growth model*, in **"The Outer Heliosphere: The Next Frontiers"**, Eds K. Scherer, H. Fichtner, H.-J. Fahr, and E. Marsch, COSPAR Colloq. Series Vol. 11, Pergamon (Holland), 125, 2001.

7. Zank, G. P., W. K. M. Rice, I. H. Cairns, J. W. Bieber, R. M. Skoug, and C. W. Smith, *Predicted timing for the turn-on of radiation in the outer heliosphere due to the Bastille Day shock*, **J. Geophys. Res.**, 106, 29,363, 2001.

8. Cairns, I.H., and M.L. Kaiser, *Solar system radio emissions*, in **"The Review of Radio Science 1999 – 2002**, Ed. W. Russ Stone, p. 749, IEEE Press, 2002.

9. Cairns, I. H., and G. P. Zank, *Turn-on of 2-3 kHz radiation beyond the heliopause*, **Geophys. Res. Lett.**, 29(7), 10.1029 2001GL014112, 47-1, 2002.

3   Presentations at Conferences or Institutions

1. **1999 Spring Meeting of the American Geophysical Union (AGU)**: *Theoretical predictions for dynamic spectra of the outer heliospheric radio emissions*, I.H. Cairns and G.P. Zank, Boston (USA), June 1999.

2. Three talks at **Goddard Space Flight Centre**, the **Bartol Research Institute**, and the **University of Iowa**: *Dynamic spectra of radio emissions from the outer heliosphere*, I.H. Cairns, June 1999.

3. **1999 Annual Meeting of the Astronomical Society of Australia**: *Progress on coronal, interplanetary, foreshock, and outer heliospheric radio emissions*, I.H. Cairns, P.A. Robinson, and G.P. Zank, Penrith (Australia), July 1999. **Invited**

4. **2000 Spring Meeting of the European Geophysical Society (EGS)**: *Radio Emissions from the Outer Heliosphere*, I.H. Cairns, Nice (France), April 2000. **Invited**

5. **COSPAR Colloquium – The Outer Heliosphere: The Next Frontier**: *Theories for Radio Emission from the Outer Heliosphere*, I.H. Cairns, Potsdam (Germany), August 2000. **Invited**

6. **COSPAR Colloquium – The Outer Heliosphere: The Next Frontier**: *Pickup Ion Turbulence: A Stochastic Growth Model*, G.P. Zank and I.H. Cairns, Potsdam (Germany), August 2000.

7. **2000 Fall AGU Meeting**: *Influence of the LISM on the Physics of the Outer Heliosphere*, G.P. Zank, H.R. Muller, W.K. Rice, and I.H. Cairns, San Francisco (USA), December 2000. **Invited**

8. **2000 Fall AGU Meeting**: *Turn-On of Radiation Beyond the Heliopause and its Propagation into the Inner Heliosphere*, I.H. Cairns and G.P. Zank, San Francisco (USA), December 2000.

9. **COSPAR / The World Space Congress 2002**: *Towards a Quantitative Theory for 2-3 kHz Emission Beyond the Heliopause*, J.J. Mitchell, I.H. Cairns, S.A. Knock, and P.A. Robinson, Houston (USA), October 2002.

10. **2002 Fall AGU Meeting**: *Semiquantitative Theory for Generation of 2-3 kHz Radiation Beyond the Heliopause*, I.H. Cairns, J.J. Mitchell, S.A. Knock, and P.A. Robinson, San Francisco (USA), December 2002.

11. **2003 Spring EGS/AGU/EGU Meeting**: *Semiquantitative Calculations of 2-3 kHz Emission from Beyond the Heliopause*, I.H. Cairns, J.J. Mitchell, S.A. Knock, and P.A. Robinson, Nice (France), April 2003.