(NASA-TM-85123) DECIMETRIC GYROSYNCHROTRON EMISSION DURING A SOLAR FLARE (NASA) 32 p HC A03/MF A01 CSCL 03B

N84-16107

Unclas
G3/92 44892

Technical Memorandum 85123

DECIMETRIC GYROSYNCHROTRON EMISSION DURING A SOLAR FLARE

David A. Batchelor
Arnold O. Benz
Herbert J. Wiehl

NOVEMBER 1983

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

DECIMETRIC GYROSYNCHROTRON EMISSION DURING A SOLAR FLARE

David A. Batchelor[1] and Arnold O. Benz[2]
Laboratory for Astronomy and Solar Physics
NASA Goddard Space Flight Center

and

Herbert J. Wiehl[3]
Institute for Applied Physics, University of Berne, Switzerland

Submitted to Astrophysical Journal
Received 1983 August 15

[1] Also Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC, and Energy/Environmental Research Group, Tucson, AZ.

[2] Permanent address: Institute of Astronomy, ETH, 8092 Zurich, Switzerland

[3] Present address: Institute of Astronomy, ETH, 8092 Zurich, Switzerland

ABSTRACT

A decimetric, microwave, and hard X-ray burst has been observed during a solar flare in which the radio spectrum below peak flux fits an f^{+2} power law over more than a decade in frequency. The spectrum is interpreted to mean that the radio emission originated in a homogeneous, thermal, gyrosynchrotron source. This is the first time that gyrosynchrotron radiation has been identified at such low decimetric frequencies (900-998 MHz). The radio emission was cotemporal with the largest single hard X-ray spike burst ever reported. The spectrum of the hard X-ray burst can be well represented by a thermal bremsstrahlung function over the energy range from 30 to 463 keV at the time of maximum flux. The temporal coincidence and thermal form of both the X-ray and radio spectra suggest a common source electron distribution. The unusual low-frequency extent of the single-temperature thermal radio spectrum and its association with the hard X-ray burst imply that the source had an area $\sim 10^{18}$ cm^2, a temperature $\sim 5 \times 10^8$ K, an electron density $\lesssim 7 \times 10^9$ cm^{-3} and a magnetic field of ~ 120 G. Hα and 400-800 MHz evidence suggest that a loop structure of length $\gtrsim$ 10,000 km existed in the flare active region which could have been the common, thermal source of the observed impulsive emissions.

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

I. INTRODUCTION

Impulsive microwave and hard X-ray bursts from solar flares often exhibit well correlated time-intensity profiles, suggesting that the emissions come from a common population of highly energetic electrons. A single distribution of energetic electrons can produce both the microwaves (hereinafter MW) via the gyrosynchrotron process and the hard X rays (HX) by collisional bremsstrahlung. Physical parameters (e.g. electron density, temperature, magnetic field strength) in the emission region can be derived from spectral analysis of both emissions under the assumption of a common source (e.g. Crannell et al. 1978). These parameters impose important constraints upon models of the emission region and the flare energy release mechanism.

In this paper we report additional coincident observations of a flare at decimetric wavelengths (DM) that permit an even more stringent constraint on the source electron density and magnetic field. Impulsive emission in the 900-998 MHz band was observed at the peak of HX and MW fluxes during the flare of 1980 March 29 at 0918 UT, and we present evidence that this DM emission represents the low-frequency extension of the impulsive gyrosynchrotron emission.

Gyrosynchrotron emission from a flare has never before been detected conclusively at such a low frequency. Our observations suggest that a common source is responsible for the HX, MW and DM emissions. We present arguments that the source is a distribution of relatively low-density thermal electrons ($n_e \lesssim 7\times10^9$ cm^{-3}) and probably is located well above the chromosphere such as at the top of a flaring loop. Medium suppression in the emitting plasma (Razin-Tsytovich effect) would severely attenuate gyrosynchrotron emission of this frequency if the source were of higher density (at lower altitudes), and distort the spectrum from its observed form.

This flare produced the largest single HX spike burst ever reported (Dennis, Frost, and Orwig 1981). The HX spectrum at the time of peak emission is in accord with a simple thermal model. We will discuss this and other evidence associating the HX and gyrosynchrotron sources with loop structures in the active region which were described by Rust et al. (1981).

II. OBSERVATIONS

The HX observations were made with the Hard X-Ray Burst Spectrometer (HXRBS) aboard the Solar Maximum Mission spacecraft (SMM). The HXRBS has been described in detail by Orwig, Frost, and Dennis (1980). The HX data were obtained with a time resolution of 0.128 s in the photon energy range 26 to 463 keV. The MW observations were made at Berne Observatory (Magun et al. 1981) with 0.1 s time resolution. The metric and DM observations were made over the frequency range 100 to 1000 MHz at the Zurich Radio Observatory (Perrenoud 1982) with 0.1 s time resolution.

This was a well-observed flare and several papers have appeared describing its properties. The relationships of the DM emission with optical and Mg XI soft X-ray observations of the flare are discussed by Rust et al. (1981). Details of the preliminary HXRBS results on this event are given by Dennis, Frost, and Orwig (1981). The flare is included in an analysis of the HXRBS and Berne observations of 13 large flares by Wiehl et al. (1983). X-ray and radio emissions in the early stages of the flare are described by Benz et al. (1983). Other observations of this flare at various wavelengths are described by Acton et al. (1981), Culhane et al. (1981) and Ryan et al. (1981).

In Figure 1, we show representative time-intensity plots of the event in DM, MW and HX. The close time relationship is obvious. The 900 to 998 MHz fluxes have been corrected for effects of antenna motion. Data collected during the brief gap in the 900 to 998 MHz trace from 0918 to 0918:05 UT were unreliable, due to the antenna motion. To calibrate the radio data, fixed frequency observations of the quiet Sun were used as references (Magun et al. 1981; Perrenoud 1980). High time resolution MW data are available at 10.4, 11.8 and 35.0 GHz and the traces are very similar to the 8.4 and 19.6 GHz curves shown in Figure 1. Observations of MW polarization (Stokes V) were also made at Berne (not shown). Below 20 GHz, the polarization was $\lesssim$ 4%; at 35 GHz it was $\lesssim$ 20%.

Flare associated emission in the 900 to 998 MHz band is often dominated by intense, broad-band pulsations which are attributed to plasma emission (e.g., Benz and Tarnstrom 1976). Pulsations in the DM continuum were prominent in this flare at frequencies from 400 to 800 MHz, as can be seen in a dynamic spectrum published by Rust et al. (1981). This flare is unusual in that the DM plasma pulsations in the 900 to 998 MHz band were weak enough to allow the impulsive DM component shown in Figure 1 to be observed. Contributions from two unrelated DM background sources have been removed from the DM fluxes shown in Figure 1. A slowly-rising continuum flux was present, growing at a constant rate of $\sim$0.2 SFU per second; at 0918:13 UT, its intensity was 47 SFU. Also, DM pulsations reaching $\sim$6 SFU were present from 0917:50 to 0918:05 UT; these pulsations were the high-frequency extensions of broad-band emissions that were most intense in the 400 to 800 MHz range, and they are therefore clearly identifiable as separate phenomena. We subtracted these two clearly separable background fluxes, and estimate that an uncertainty of ±0.6 SFU is thereby introduced in the remaining flux. This uncertainty is negligible when compared with the instrumental calibration uncertainty of ±24% in the 900 to 1000 MHz range (Perrenoud 1982). Consequently, we report that the impulsive DM flux attained a peak value of 9.3 ± 2.9 SFU at 0918:13 UT, within 1 s of the peak time of the MW emissions.

The emission mechanism responsible for MW bursts at frequencies above 3 GHz is generally held to be the gyrosynchrotron process (Kundu 1965). On the basis of the spectrum shown in Figure 2 and the close time relationship of the impulsive DM and MW emissions, we identify the impulsive DM component as the observed low-frequency limit of gyrosynchrotron emission from this flare. In Figure 2, it can be seen that the fluxes at 950 MHz, 8.4 GHz and 10.4 GHz are consistent with an f^{+2} dependence (where f is the frequency), characteristic of optically-thick emission from a thermal source. This spectrum is interpreted in more detail in Section III.

III. PHYSICAL CONDITIONS IN THE GYROSYNCHROTRON SOURCE

The spectral characteristics of thermal and nonthermal (power-law) gyrosynchrotron sources are well known (Ramaty 1969; Matzler 1978). Observed flare spectra such as that of Figure 2 are known as C-type (Guidice and Castelli 1975). The spectral index at low frequencies ranges from 0 to 3, with the most common value of 1.4 (Schochlin and Magun 1979). This part of the spectrum is attributed to optically-thick or self-absorbed emission. The maximum flux occurs at some peak frequency, f_{max}, and there is a portion at higher frequencies for which the source is thought to be optically-thin, associated with a negative slope.

The optically-thick portion of Figure 2 is fit well by the simple Rayleigh-Jeans law characteristic of a homogeneous, thermal source (cf. Crannell et al. 1978),

$$S(f) = 1.36x10^{-44} f^{2} A T \qquad (1)$$

where S is the MW flux in SFU (10^{-22} W m^{-2} Hz^{-1}), f is the frequency in Hz, A is the source area in cm^{2} and T is the source temperature in degrees K. This relationship is illustrated in Figure 2 by the dashed line. The small values of polarization ($\lesssim$ 4%) observed in this part of the spectrum are consistent with optically-thick emission.

The high-frequency part of Figure 2 does not correspond to the optically-thin spectrum of a homogeneous, thermal source. The slope above f_{max} should be in the range -5 to -10 (Matzler 1978); instead the flux falls much more slowly from its peak value. One possible explanation is that the source is inhomogeneous in temperature and/or magnetic field strength (cf. Dulk and Dennis 1982). This could happen in a flaring loop in which the field strengthens near the footpoints. Two-dimensional VLA maps of solar MW bursts support this explanation (Marsh and Hurford 1980; Marsh et al. 1980; Kundu, Bobrowsky and Velusamy 1981; Marsh et al. 1981). It is also possible that there is a suprathermal tail in the electron distribution with energies of order 1 MeV (Marsh et al. 1981). The γ-ray observations of this flare reported by Ryan et al. (1981) suggest that there might be such a suprathermal tail. Neither of these explanations of the spectrum above f_{max} invalidates the interpretation of the spectrum at and below f_{max} which follows.

We assume in the remainder of this paper that a single-temperature source dominates the emission at frequencies below f_{max}, and that the radiation is gyrosychrotron emission. These assumptions allow us to derive its properties.

Emission in a magnetized plasma at frequencies below the first three harmonics of the electron cyclotron frequency, $f_B = 2.8\times10^6$ B (Hz), is strongly absorbed. Since we see emission at less than 1 GHz, it follows that B must be $\lesssim$ 120 G. Propagation also is not possible at frequencies below the electron plasma frequency $f_{pe} = 9\times10^3\ n_e^{0.5}$, which implies that $n_e \lesssim 1.2\times10^{10}\text{cm}^{-3}$. A final condition that follows from the observation of thermal gyrosynchrotron flux in the 900 to 998 MHz band is derived from the absence of medium suppression, the Razin-Tsytovich effect (Ginzburg and Syrovatskii 1965). This effect, if present, would produce a low-frequency cut-off in the spectrum. There is no suppression if

$$f \gtrsim 20\ n_e/(B \sin \theta), \qquad (2)$$

where θ is the angle of the field B with respect to the observer's line of sight. The cut-off must be below 900 MHz, so $B \sin \theta \gtrsim 2\times10^{-8}\ n_e$.

The HX emission also provides information about the electron distribution in the flare. A spectrum of the flare has been published by Wiehl et al. (1983, Figure 31). At the time of maximum flux (0918:12.36-0918:13.36 UT), a thermal bremsstrahlung function with $T = 5\times10^8$ K is an acceptable fit to the HX spectrum for the energy range 30 to 463 keV (as determined by the χ^2 statistic: $\chi^2 = 8.7$ for 12 degrees of freedom). A single power law was unacceptable (χ^2 several orders of magnitude larger).

A plasma of temperature 5×10^8 K can be optically thick at MW frequencies in our observing range under the present conditions on B and n_e (Matzler 1978). This fact and the close time correlation of the MW and HX emissions (Figure 1) suggest that such a plasma was the source of both emissions. Following Crannell et al. (1978), we take the HX peak temperature to be characteristic of the source electrons at the same time. Then Equation (1) yields an area of 1.3×10^{18} cm^2, implying a characteristic size of the source, $\sim10^9$ cm, within a factor of order unity dependent on the geometry.

We also know $f_{max} \cong 10.4$ GHz (see Figure 2). Knowing the source size, we can derive stronger conditions on n_e and B, making use of the simplified expression for f_{max} given by Dulk and Marsh (1982),

$$f_{max} = 1.8\ (n_e L/B)^{0.1} (\sin\theta)^{0.6} T^{0.7} B \qquad (3)$$

where L is the source thickness in cm. Eliminating B with the condition for no medium suppression, Equation (2), we can rearrange Equation (3) to get

$$n_e \lesssim 6.1 \times 10^{6}\ f_{max}\ L^{-0.1} (\sin\theta)^{0.3}\ T^{-0.7}. \qquad (4)$$

Substituting $f_{max} = 10^{10}$ Hz (Figure 2), $T = 5.1 \times 10^{8}$ K, $\theta = 80^{\circ}$ and $L = 10^{9}$ cm, we find $n_e \lesssim 7 \times 10^{9}$ cm^{-3}. This upper limit on n_e is not very sensitive to L, but reducing θ could reduce it somewhat. Taking $\theta = 60^{\circ}$ would only reduce the upper bound on n_e by 3%. Reasons for taking $60^{\circ} < \theta < 90^{\circ}$ are discussed in Section IV. The density in the source can be much smaller than the calculated upper limit, or even vary within the source from point to point. This is because the emission is optically thick, so that the part of the spectrum under consideration depends only on f, A and T (Equation 1), and on f_{max}, which is very insensitive to n_e (Equation 3).

Alternatively, we can eliminate n_e with Equation (2). This yields

$$B \gtrsim 0.12\, f_{max}\, L^{-0.1} (\sin\theta)^{-0.7}\, T^{-0.7} . \qquad (5)$$

With the same substitutions as above, we find $B \gtrsim 120$ G. From previous considerations of cyclotron harmonics, we found that $B \lesssim 120$ G. These results are consistent for $B \cong 120$ G, within the uncertainties of Equation (3). The derived limits on n_e and B describe a plasma with $\beta = 8\pi n_e k\, T/B^2 \lesssim 0.71$, a high value, but the field is still capable of confining the plasma.

Another measurement of the density is possible if we assume that the HX and gyrosynchrotron sources are identical, and occupy a volume, V. The emission measure, $n_e^2 V = 4\times10^{45}$ cm^{-3}, was also derived from the HX spectrum. If $V = A^{1.5}$, where A is the gyrosynchrotron source area calculated above, then $n_e = 2\times10^9$ cm^{-3}. This is consistent with our earlier estimate which was independent of the HX emission measure.

The total energy in the source can be computed from these source parameters. The thermal energy density is $3\, n_e k\, T/2$ (assuming that the electrons are much hotter than the ions). We deduced from Equation (4) that $n_e \lesssim 7\times10^9$ cm^{-3}, which implies an energy density $\lesssim$ 600 erg cm^{-3}, and an instantaneous total energy $\lesssim 10^{30}$ erg. If $V_{HX} = V_{MW} = 10^{27}$ cm^3, then $n_e = 2\times10^9$ cm^{-3}, giving 200 erg cm^{-3} and 3×10^{29} erg, total energy.

The density range and temperature of the thermal electrons in the gyrosynchrotron source imply a Coulomb self-collision time > 12 s (Crannell <u>et al.</u> 1978), approximately the duration of the burst. Thus, if the SX and gyrosynchrotron source regions were identical, then the electrons could not have been thermalized by Coulomb collisions alone in the source region. Several possible mechanisms exist for producing a quasi-Maxwellian electron distribution with such a high temperature. Thermalization could occur via ion-acoustic turbulence, perhaps in a collisionless conduction front (Brown, Melrose and Spicer 1979).

ORIGINAL PAGE IS
OF POOR QUALITY

IV. COMPARISON OF OPTICAL, RADIO AND HARD X-RAY OBSERVATIONS

Other observations of the flare are helpful in understanding the origin of the HX- and DM/MW-emitting electrons and their role in the flare. Here we briefly summarize the Hα observations of this flare reported by Rust _et al._ (1981). The flare took place in a region of emerging magnetic flux. In an Hα picture obtained at Hvar Observatory at 0920 UT, a faint loop is seen connecting two bright kernels ∿2000 km in diameter, which were located about 7000 km apart in areas of opposite magnetic polarity. Another diffuse brightening is seen $1\text{-}2\times10^4$ km NW of the Hα loop and the existence of a loop structure of this size was inferred, connecting the diffuse brightening with the visible Hα loop.

Pertinent radio observations of the flare are described by Rust _et al._ (1981) and Benz _et al._ (1983). DM continuum emission in the 400 to 800 MHz band commenced at 0917:20 UT and continued until well after the time of the HX peak. There were also type III radio bursts with starting frequencies in the 200 to 400 MHz band during the HX emission, with three spatially distinct components which were imaged with the Nançay radioheliograph. Rust _et al._ concluded that the preflare heating started at 0917 UT in the 7000 km loop and that energetic electrons escaped from there into larger structures at the peak of the impulsive HX emission, resulting in the DM continuum activity and Type III bursts.

The last observation of this flare which we wish to consider here is the 3.5 to 30 keV image recorded by the Hard X-ray Imaging

Spectrometer (HXIS, described by Van Beek et al. 1980) on SMM. The location and size of the X-ray source in this energy range were determined with a resolution of 32" (corresponding to 23,000 km on the Sun), as the flare was detected in the HXIS coarse field of view. The source was less than or equal to one resolution element in size. A diagram showing the source position relative to features of the active region is provided by Benz et al. (1983, Figure 5(a)). The location of the 3.5 to 30 keV X-ray source is consistent with the position of such a large loop, as can be seen by comparing the Hα image (Rust et al. 1981) with the diagram of the active region.

V. INTERPRETATION

As there are no high-resolution images of this event available in HX or MW, we must generalize from imaging observations of other flares for the interpretation of our results. By means of observations of flares made with the Very Large Array (VLA), investigators have located MW burst sources approximately over the neutral line of photospheric magnetic fields, and have inferred that the sources lie near the tops of loops (cf. Marsh and Hurford 1982; Kundu 1982). The size, density range and magnetic field that we deduced in Section III for the DM/MW gyrosynchrotron source are appropriate for large loop(s) connecting the region of the 7000 km loop and Hα kernels with the diffuse Hα patch ∿10,000 km NW. We therefore suggest that the source of this DM/MW burst was near the apex of such a large loop. Inspection of the Hα image provided by Rust et al. (1981) suggests that we view the top of the inferred DM/MW source loop from an angle between 90° and 60°. Within this range, the angle θ does not vary our bounds on n_e and B significantly.

In Section III., we made the simplifying assumption of a common source for the HX and MW emissions. The HXIS position of the flare is consistent with this assumption, but we cannot infer the detailed structure of the present HX source because HX imaging observations of flares do not reveal a consistent structure. Some observations made with the HXIS on SMM (Hoyng et al. 1981; Duijveman, Hoyng and Machado 1982) indicate that simultaneous impulsive brightenings occur with spatial separations too large to be explained without invoking collisionless electron beams. The HX emission in those cases appeared to come from loop footpoints, as in the thick-target model (Brown 1971; Hoyng, Brown, and Van Beek 1976). However, observations of 10 impulsive flares made with the Solar hard X-ray Telescope on the Hinotori spacecraft (SXT, described by Makishima 1982) revealed single, compact sources in almost all cases, according to Takakura et al. (1983). The energy range (17 to 60 keV) and spatial resolution (~10") of SXT are similar to those of HXIS. Thus, there appears to be a diversity of HX source morphology among flares. A comparison of VLA and HXIS observations of one small flare has been published by Hoyng et al. (1983). In that flare, the MW source had a smaller projected area than the HX source and there was some evidence against a common source for the two emissions. On the other hand, some evidence for a common source of HX emission and the MW flux near f_{max} was given by Wiehl et al. (1983) from observations of another flare . In analyzing the flare of 1981 August 10 at 0659 UT, Wiehl et al. made the assumption of a common HX and MW source and computed the source area using the procedure we used in the present paper. The flare of August 10 had been observed with SXT in the energy range from 17 to 40 keV (Ohki et al. 1982), and it was found that the observed and derived source areas agreed, within the uncertainties. More comparisons of coincident HX and MW images are needed to determine whether the assumption of a common source is generally valid. The MW and HX images may not correspond exactly because of the effects of viewing angle and magnetic field gradients on the MW emission, but the source electron populations may still be the same.

VI. SUMMARY AND CONCLUSIONS

We have reported and discussed the implications of high time-resolution observations of a decimetric, microwave, and hard X-ray burst during a solar flare in which the 900 to 998 MHz, 8.4 GHz, and 10.4 GHz peak fluxes fit the optically-thick spectrum of a homogeneous, thermal gyrosynchrotron source. The hard X-ray spectrum from 30 to 463 keV is well represented by a thermal bremsstrahlung function, and we have used a temperature derived from this spectrum to find the source area, $\sim 10^{18}$ cm^2. Elementary plasma physics considerations and the lack of Razin-Tsytovich absorption of the 900 to 998 MHz flux allow us to deduce that $n_e \lesssim 7\times10^9$ cm^{-3} and $B \cong 120$ G. These conditions place the gyrosynchrotron source at high altitude in a coronal loop, in agreement with VLA observations of other flares. Hα and 400 to 800 MHz observations of this flare were used by Rust et al. (1981) to infer the existence of just such a loop structure, and other X-ray and radio evidence published by Benz et al. (1983) support our interpretation.

This flare (1980 March 29, 0918 UT) was the largest single hard X-ray spike burst ever reported, with a peak flux of 6 photons cm^{-2} s^{-1} keV^{-1} (Dennis, Frost, and Orwig 1981). It also was classified as a Great Burst in the microwave range, exceeding 1000 SFU. Intense, impulsive flares are commonly characterized as nonthermal events, despite statistical evidence that the hard X-ray spectra at the peak of most bursts fit a thermal function rather than a power law (Crannell et al. 1978; Elcan 1978; Ohki *et al.* 1983; Wiehl *et al.* 1983). However, the parameters (n_e and B) derived herein from a simple thermal model are consistent with current knowledge of physical conditions in active regions, and with the features of the active region responsible for the present flare.

This work demonstrates the continuing importance of thermal models, and suggests that further theoretical investigations of them should be undertaken, particularly of the properties of the microwave emission.

ORIGINAL PAGE IS
OF POOR QUALITY

ACKNOWLEDGEMENTS

We wish to thank B. R. Dennis, L. E. Orwig and K. J. Frost for access to the HXRBS data. C. J. Crannell provided valuable comments and direction. We are also grateful to A. L. Kiplinger, A. K. Tolbert, H. E. Dennis, B. E. Gibson and G. S. Kennard for essential guidance in the use of the HXRBS data analysis software at NASA-GSFC, and to P. N. Price for a critical reading of the manuscript. We also thank an anonymous referee for useful suggestions. This work was supported in part by NSG 5066. One of us (DAB) was supported under NAS 5 26341. HJW was supported in this work by the Swiss National Science Foundation. AOB was a senior research associate of the U.S. National Research Council (NAS) during most of this work. The construction of the Berne and Zurich radio observatories was partially supported by the Swiss National Science Foundation.

REFERENCES

Acton, L. W., Culhane, J. L., Gabriel, A. H., Wolfson, C. J., Rapley, C. G., Phillips, K. J. H., Antonucci, E., Bentley, R. D., Hayes, R. W., Joki, E. G., Jordan, C., Kayat, M. A., Kent, B., Leibacher, J. W., Nobles, R. A., Parmar, A. N., Strong, K. J., and Veck, N. J. 1981, *Ap. J.*, **244**, L137.

Benz, A. O., Barrow, C., Dennis, B. R., Pick, M., and Simnett, G. 1983, *Solar Phys.*, **83**, 267.

Benz, A. O., and Tarnstrom, G. L. 1976, *Ap. J.*, **204**, 597.

Brown, J. C. 1971, *Solar Phys.*, **18**, 489.

Brown, J. C., Melrose, D. B., and Spicer, D. S. 1979, *Ap. J.*, **228**, 592.

Crannell, C. J., Frost, K. J., Matzler, C., Ohki, K., and Saba, J. L. 1978, *Ap. J.*, **223**, 620.

Culhane, J. L., Gabriel, A. H., Acton, L. W., Rapley, C. G., Phillips, K. J., Wolfson, C. J., Antonucci, E., Bentley, R. D., Catura, R. C., Jordan, C., Kayat, M. A., Kent, B. J., Leibacher, J. W., Parmar, A. N., Sherman, J. C., Springer, L. A., Strong, K. T., and Veck, N. J. 1981, *Ap. J.*, **244**, L141.

Dennis, B. R., Frost, K. J., and Orwig, L. E. 1981, *Ap. J.*, **244**, L167.

Duijveman, A., Hoyng, P., and Machado, M. E. 1982, *Solar Phys.*, **81**, 137.

Dulk, G. A., and Dennis, B. R. 1982, *Ap. J.*, **260**, 875.

Dulk, G. A., and Marsh, K. A. 1982, *Ap. J.*, **259**, 350.

Elcan, M. J. 1978, *Ap. J.*, **226**, L99.

Ginzburg, V. L., and Syrovatskii, S. I. 1965, *Ann. Rev. Astr. Ap.* (Palo Alto, CA: Ann. Rev., Inc.), **3**, 297.

Guidice, D. A., and Castelli, J. P. 1975, *Solar Phys.*, **44**, 155.

Hoyng, P., Brown, J. C., and Van Beek, H. F. 1976, *Solar Phys.*, **48**, 197.

Hoyng, P., Duijveman, A., Machado, M. E., Rust, D. M., Svestka, Z., Boelee, A., de Jager, C., Frost, K. J., Lafleur, H., Simnett, G. M., van Beek, H. F., and Woodgate, B. E. 1981, *Ap. J.*, **246**, L155.

Hoyng, P., Marsh, K. A., Zirin, H., and Dennis, B. R. 1983, *Ap. J.*, **268**, 865.

Kundu, M. R. 1965, *Solar Radio Astronomy* (New York: Wiley Interscience).

Kundu, M. R. 1982, *Reports on Progress in Phys.*, **45**, 1435.

Kundu, M. R., Bobrowsky, M., and Velusamy, T. 1981, *Ap. J.*, **251**, 342.

Magun, A., Fuhrer, M., Kaempfer, N., Staehli, M., Schoechlin, W., Wiehl, H. 1981, Institute of Applied Physics Report 46, University of Berne.

Makishima, K. 1982, *Proc. Hinotori Symp. on Solar Flares* (Tokyo: Inst. Sp. Astronaut. Sci.), p. 120.

Marsh, K. A., and Hurford, G. J. 1980, *Ap. J.*, **240**, L111.

Marsh, K. A., and Hurford, G. J. 1982, *Ann. Rev. Astron. Ap.* (Palo Alto, CA: Ann. Rev., Inc.), 497.

Marsh, K. A., Hurford, G. J., Zirin, H., Hjellming, R. M. 1980, *Ap. J.*, **242**, 352.

Marsh, K. A., Hurford, G. J., Zirin, H., Dulk, G. A., Dennis, B. R., Frost, K. J., and Orwig, L. E. 1981, *Ap. J.*, **251**, 797.

Matzler, C. 1978, *Astron. Astrophys.*, **70**, 181.

Ohki, K., Takakura, T., Tsuneta, S., and Nitta, N. 1983, in *Recent Advances in the Understanding of Solar Flares*, ed. Y. Uchida, S. R. Kane, H. S. Hudson, and K. Tanaka, to be published as a special issue of *Solar Phys.*, 1983.

Ohki, K., Tsuneta, S., Takakura, T., Nitta, N., Makishima, K., Ogawara, Y., Oda, M., and Miyamoto, S. 1982, *Proc. Hinotori Symp. on Solar Flares* (Tokyo: Inst. Sp. Astronaut. Sci.), p. 102.

Orwig, L. E., Frost, K. J., and Dennis, B. R. 1980, *Solar Phys.*, **65**, 25.

Perrenoud, M. R. 1982, *Solar Phys.*, **81**, 197.

Ramaty, R. 1969, *Ap. J.*, **158**, 753.

Rust, D. M., Benz, A., Hurford, G. J., Nelson, G., Pick, M., and Ruzdjak, V. 1981, *Ap. J.*, **244**, L179.

Ryan, J. M., Forrest, D. J., Chupp, E. L., Cherry, M. L., Reppin, C., Rieger, E., Pinkau, K., Kanbach, G., Share, G. H., Kinzer, R. L., Strickman, M. S., Johnson, W. N., and Kurfess, J. D. 1981, *Ap. J.*, **244**, L175.

Schochlin, W., and Magun, A. 1979, *Solar Phys.*, **64**, 349.

Takakura, T., Ohki, K., Tsuneta, S., and Nitta, N. 1983, in *Recent*

Advances in the Understanding of Solar Flares, ed. Y. Uchida, S. R. Kane, H. S. Hudson, and K. Tanaka, to be published as a special issue of *Solar Phys.*, 1983.

Van Beek, H. F., Hoyng, P., Lafleur, B., and Simnett, G. M. 1980, *Solar Phys.*, **65**, 73.

Wiehl, H. J., Batchelor, D. A., Crannell, C. J., Dennis, B. R., and P. N. Price 1983, NASA Tech. Memo. 85052; condensed and submitted to *Solar Phys.*

FIGURE CAPTIONS

Figure 1.--Representative time profiles of the impulsive solar flare of 1980 March 29, 0918 UT.

Figure 2.--Composite spectrum of the flare at the time of peak hard X-ray emission (0918:13 UT). Filled circles represent observations made at Berne. The cross represents the Zurich observation and uncertainty.

NAMES AND ADDRESSES OF AUTHORS

D. A. Batchelor: Code 684, NASA Goddard Space Flight Center, Greenbelt, MD 20771

A. O. Benz and H. J. Wiehl: Institute of Astronomy, ETH, 8092 Zurich, Switzerland

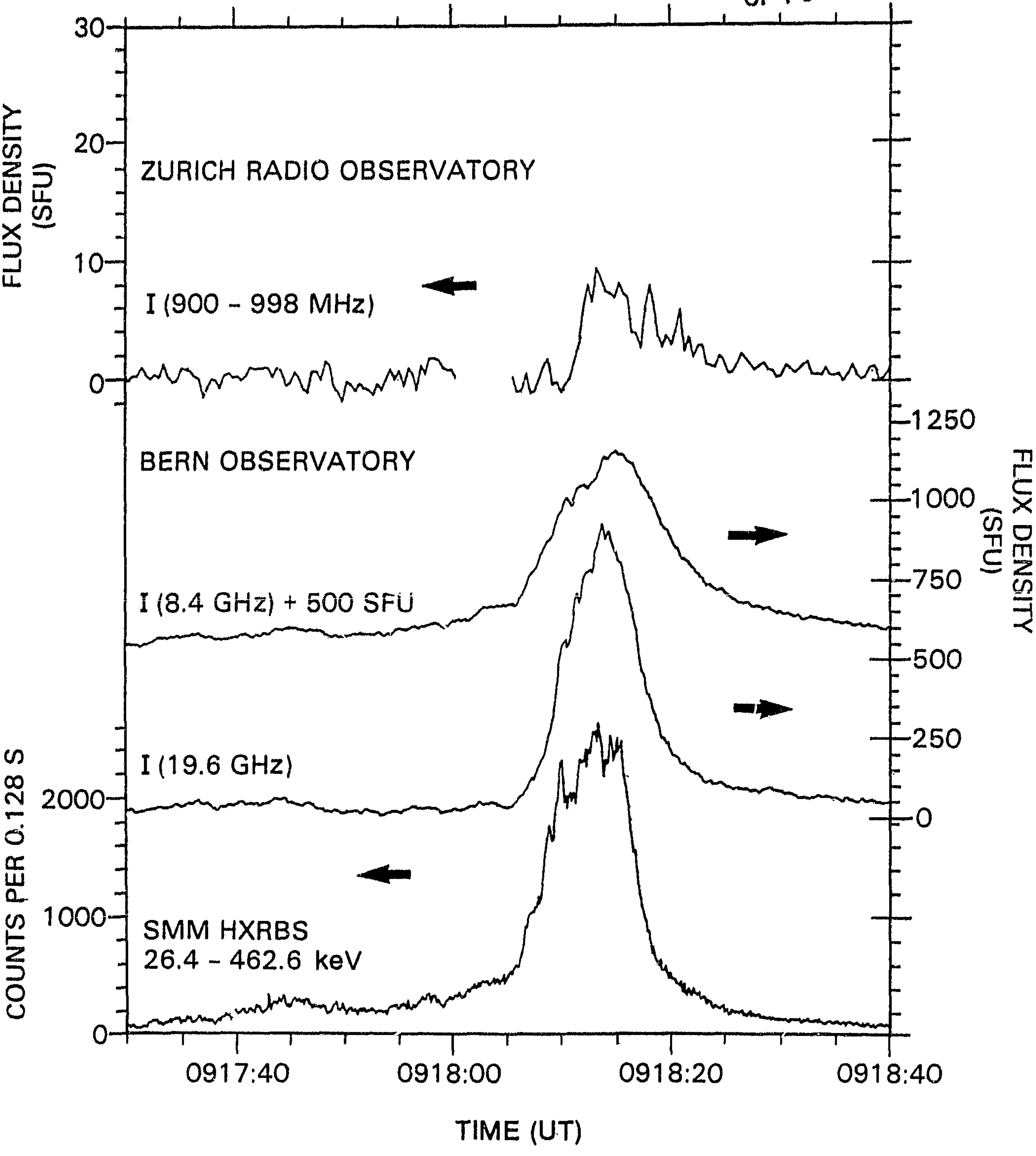
30
20
10
0
FLUX DENSITY (SFU)
ZURICH RADIO OBSERVATORY
I (900 - 998 MHz)
BERN OBSERVATORY
I (8.4 GHz) + 500 SFU
I (19.6 GHz)
1250
1000
750
500
250
0
FLUX DENSITY (SFU)
2000
1000
0
COUNTS PER 0.128 S
SMM HXRBS
26.4 - 462.6 keV
0917:40
0918:00
0918:20
0918:40
TIME (UT)

Figure 1

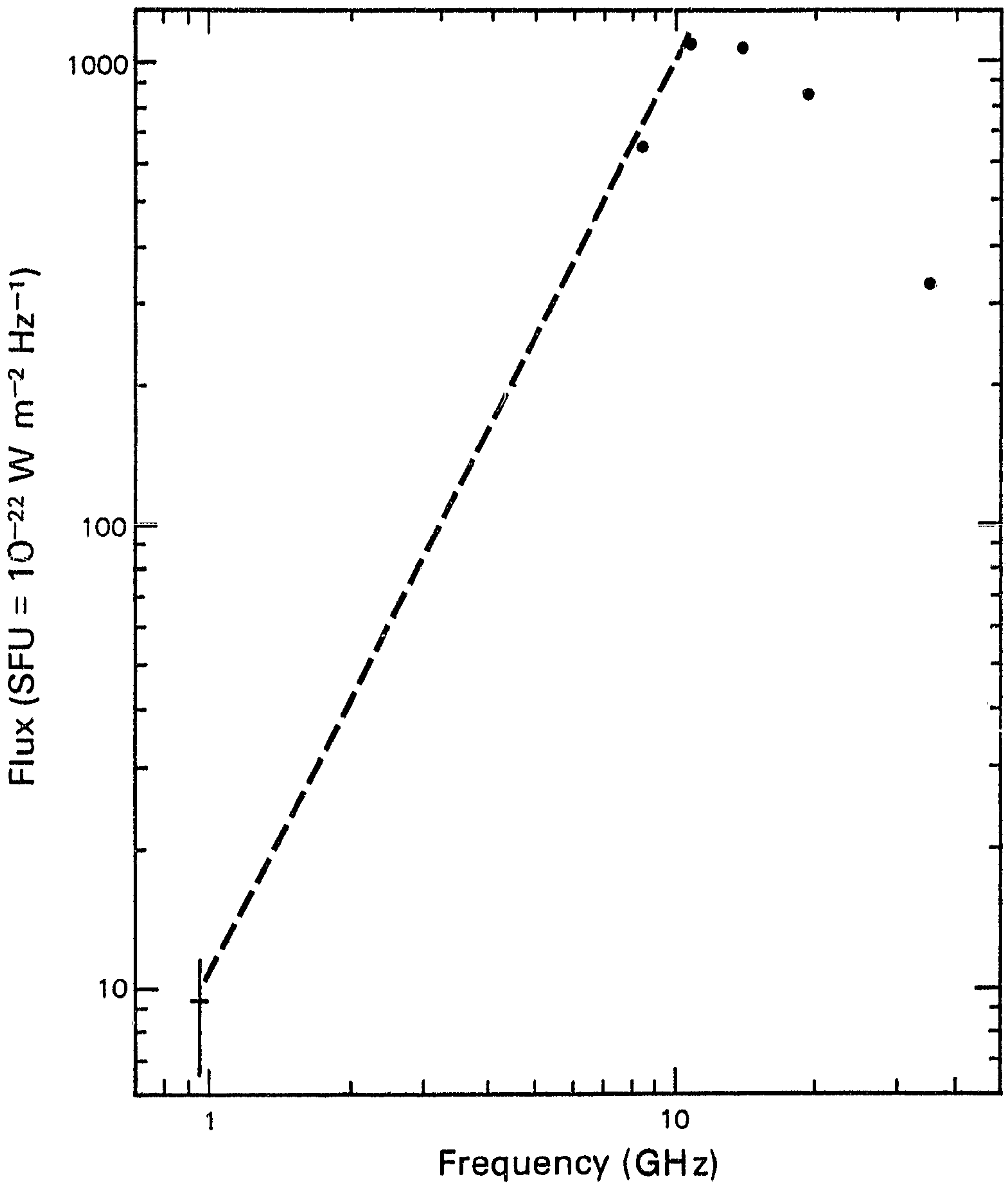

Figure 2