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Letter to the Editor

An active solar prominence in 1.3 mm radiation

R. A. Harrison[1], **M. K. Carter**[1], **T. A. Clark**[2], **C. Lindsey**[3], **J. T. Jefferies**[4], **D. G. Sime**[5], **G. Watt**[6], **T. L. Roellig**[7], **E. E. Becklin**[8], **D. A. Naylor**[9], **G. J. Tompkins**[9], **and D. Braun**[3]

[1] Astrophysics Division, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK
[2] University of Calgary, Department of Physics and Astronomy, 250 University Drive NW, Calgary, AB T2N 1N4, Canada
[3] Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
[4] National Optical Astronomy Observatories, 950 N. Cherry Ave., Tucson, AZ 85726, USA
[5] High Altitude Observatory, National Center for Atmospheric Research, PO Box 3000, Boulder, Colorado 80307, USA
[6] Joint Astronomy Centre, 665 Komohana St., Hilo, HI 96720, USA
[7] NASA/Ames Research Center, Mailstop 245-6, Moffett Field, California 94035, USA
[8] University of California at Los Angeles, Department of Astronomy, Los Angeles, CA 90024, USA
[9] University of Lethbridge, Department of Physics, Lethbridge, AB T1K 3M4, Canada

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Abstract. We present new millimetre-wavelength observations of an active solar prominence. Observations made over a two-day period with the James Clerk Maxwell Telescope on Mauna Kea, Hawaii, give a unique view in 1.3 mm radiation of the spectacular prominence that appeared on the west solar limb in the total solar eclipse of 11 July 1991.

Key words: Sun - prominence - radio

1. Introduction

We report the first millimetre observations of an active solar prominence, made with the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. This spectacular feature, extending more than 75,000 km above the solar photosphere, was well observed by a large number of instruments throughout the western hemisphere because of its striking appearance on the west limb of the Sun during the total solar eclipse of 11 July 1991. The unexpected appearance of the prominence during preparations to observe a total solar eclipse over the world's largest submillimeter telescope, as it passed directly over the JCMT, on Mauna Kea, Hawaii, gave us the opportunity to study a most unusual apparition in detail over the spectral range extending from 0.8 to 2.0 mm, in which prominences have not previously been observed. Observations in this range generally need to be made from high-altitude dry sites, such as Mauna Kea, since the primary source of opacity in the terrestrial atmosphere is water vapour.

Solar prominences are believed to consist of material at densities of about 10^{10}-10^{12} cm^{-3} with temperatures of about 5,000 K to 10,000 K. They extend tens of thousands of km above the chromosphere into the surrounding, much hotter and much more tenuous, corona. Many prominences are quiescent, showing little change for days or even weeks. Some are active or unstable, occasionally erupting with the overlying corona. Much remains to be understood about prominences and their relation to the overlying corona. Recent reviews include Ruzdjak and Tandberg-Hanssen (1990) and Priest (1989).

Submillimetre and millimetre continuum observations offer a new and powerful diagnostic of the physical conditions in prominences, particularly where thermal considerations are of interest. The emission is probably almost entirely free-free, caused by free electrons colliding with ions. For optically thick features, this emission serves as an excellent thermometer, its brightness being simply proportional to the temperature of the emitting gas (see Deming *et al.* 1990).

Observations have been made previously at cm and mm wavelengths of quiescent filament structures viewed against the solar disc (see review by Hiei *et al.* 1986). In these data, the filaments appear dark against the disc longward of 3 mm, just as they do in images made in visible chromospheric lines, such as Hα. While mm continuum observations contain information on temperature which is difficult to derive from the visible line observations made conventionally, the radio data are most effective when complemented by these observations. In particular, the mm observations to date have lacked the high spatial resolution routinely available with observations in the visible. The result is that it has been difficult to discriminate these structures at the limb and to resolve the filament structure from any possible surrounding structure such as the filament cavity when they are viewed on the disc. In addition, derivation and interpretation of physical diagnostics from mm results should also be guided by the knowledge gained from visible imaging. Hα images show that prominences are highly inhomogeneous. The material which emits in Hα shows a filamentary structure showing dark lanes. These features, although unresolved in the mm continuum, indicate that the underlying structure has a filling factor which is significantly less than one, and this point must be accounted for when the interpretation of the mm data is made.

2. Observations

The JCMT is a 15 m reflecting telescope designed to detect radiation as short as 0.35 mm. It is located near the summit of Mauna Kea, Hawaii, at an elevation of 4,092 m.

Further details on the telescope and results of the first solar observations using the JCMT have been described by Lindsey et al. (1990). For the observations reported here, we used the facility's Receiver-A, a heterodyne detector tuned to 248 GHz or 1.3 mm, with a band-width of 500 MHz. The diffraction-limited beam width at this wavelength is 21″. The prominence was discovered on 10 July 1991 during preparations to observe the solar limb occultation by the moon (see Lindsey *et al.* 1992). We operated the JCMT in a raster-scanning mode to image selected regions of the solar limb in the neighbourhood of the prominence. The images we show here consist of 60 scans in elevation separated by 10″, each made over a 9 min period.

Figure 1 shows images made this way on 10 July 1991 at (a) 18:33 and (b) 19:35, and on 11 July 1991 at (d) 19:25 UT. Frame (c) shows the prominence in Hα taken from the Mauna Loa Solar Observatory at 18:52 UT on 10 July. Similarly, frames (e) and (f) show the Hα prominence at 19:05 and 19:08 UT, respectively, on 11 July 1991. The latter is taken from an image made with the disc of the photosphere occulted. For both the mm and Hα data sets, the colour table has been designed to make the fainter prominence features visible simultaneously with the more intense disc features. On the disc we see a mottled pattern, which is unchanging from image to image, similar to that reported by Lindsey et al. (1990). Above the limb, we see the large, bright prominence. On 10 July, it resembles an "S" shape attached to the Sun at one point some 9° north of the western equator. Two intense concentrations of emission dominate the prominence. For clarity we will call these the southern and northern patches. These brighter portions of the prominence cover more than 10^5km in horizontal extent, reaching altitudes up to 75,000 km. A bridge connects the northern and southern patches and some diffuse emission appears to the south.

There are significant changes between 10 and 11 July: The northern patch has disappeared, while the southern patch appears compacted and slightly lower, as if having partially set behind the limb. Clearly visible above the southern patch is a weak enhancement, possibly part of an overlying loop structure. It reaches a projected altitude of 83,000 km.

The Hα frames show a similar story. However, the frame with the occulted disc, which was exposed through at 6Å bandwidth, shows much more detail. Hα images made the next day showed no prominence; it is thought to have erupted.

In Figure 2 we plot brightness profiles measured at 1.3 mm as the JCMT beam was scanned through the prominence. Panel (a) shows the profiles taken from rows 5, 19, 26 and 38 of Panel (a) of Figure 1 (see numbered fiducials on that frame). These scans pass through the north of the prominence, through the northern and southern patches, and through the weak brightening to the south, respectively.

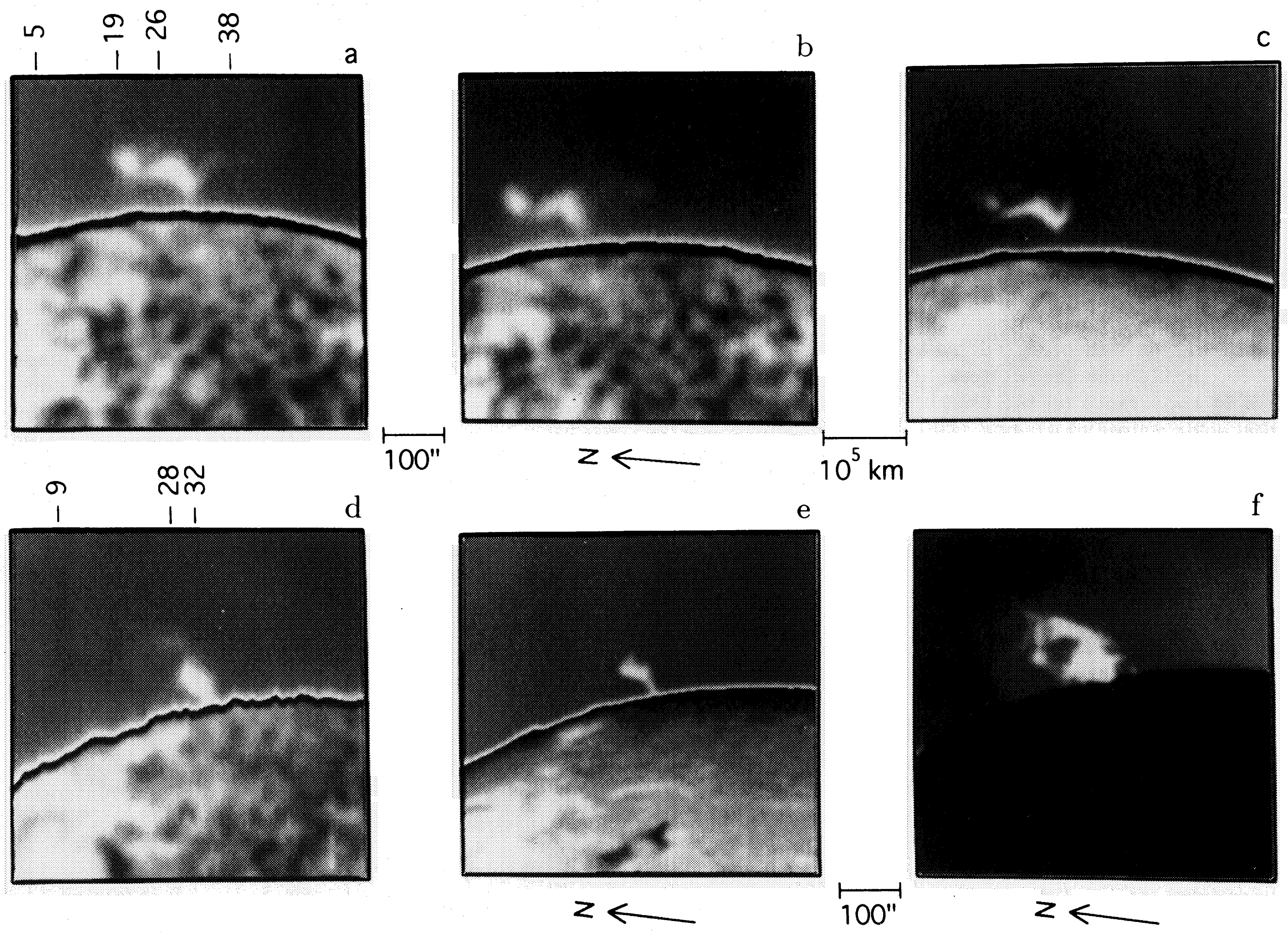

Fig. 1. 1.3mm images taken at (a) 18:33, (b) 19:35 on 10 July 1991, and (d) 19:25 on 11 July 1991. Hα images taken at (c) 18:52 on 10 July 1991, (e) 19:05 and (f) 19:08 on 11 July 1991. In frame (f) the photosphere is occulted

The northernmost scan (solid curve) misses the prominence, showing only the quiet limb. The tail extending upward from the limb is due to contamination by disc radiation through the far wings of the JCMT beam profile. The 1.3 mm emission arising from the ambient corona in this vicinity is negligible. The other scans pass through the two bright patches, and through the weak prominence emission to the south.

The absence of coronal emission is clarified by the plot in Panel (b), showing a scan through the prominence 23 hr later, during total eclipse, at 10 times the gain of the plots in Panel (a). The plateau to the left of the plot is the lunar profile ($\approx$100 K), extending some $62''$ beyond the solar limb. The appearance of the prominence against the lunar horizon 45,000 km above the solar limb takes the signal off scale until it returns to a nearly flat baseline well above 100,000 km. Outside of this extended emission, which we attribute to the high extremity of the prominence there appears no evidence of signal due to extended coronal structure. Panel (c) plots the intensity in columns 9, 28 and 32 of Panel (a) in Figure 2 (see numbered fiducials in that Panel). These scans show the quiet limb, the southern patch and the overlying feature, and the heart of the southern patch.

Returning to Figure 1, the intensity of the northern and southern patches is relatively constant, at 0.40 ± 0.02 times the disc intensity, a brightness temperature of 2,200 K if we assume a solar disc brightness temperature of 5,400K, after Model C of Vernazza *et al.* (1976). The principal brightening of frame (d), on the next day, is significantly brighter, approximately 0.57 times the disc intensity, giving a brightness temperature of 3,100 K.

3. Discussion

The disappearance of the northern patch between 10 and 11 July could possibly be explained by its simply setting. Geometrical considerations suggest that this is improbable, since they require it to be some 25° beyond the southern patch in longitude (300,000 km). More plausible is that the northern patch simply is no longer at this altitude due to evaporation, draining or even a partial eruption.

Information presently at our disposal is insufficient to give us both the density and temperature of the prominence unambiguously, even if these could be assumed uniform throughout the structure. Unable to observe this feature against the solar disc, we cannot unambiguously estimate both its opacity and overall temperature. Let us assume a path length of order 40,000 km as the thickness over which the most intense emission emanates, i.e. similar to the projected widths of the most intense cores of the north and south patches. Accepting an electron temperature of 6500 K (Hirayama, 1985) demands an electron density of less than 10^{10}cm^{-3}. On the other hand, forcing a density of

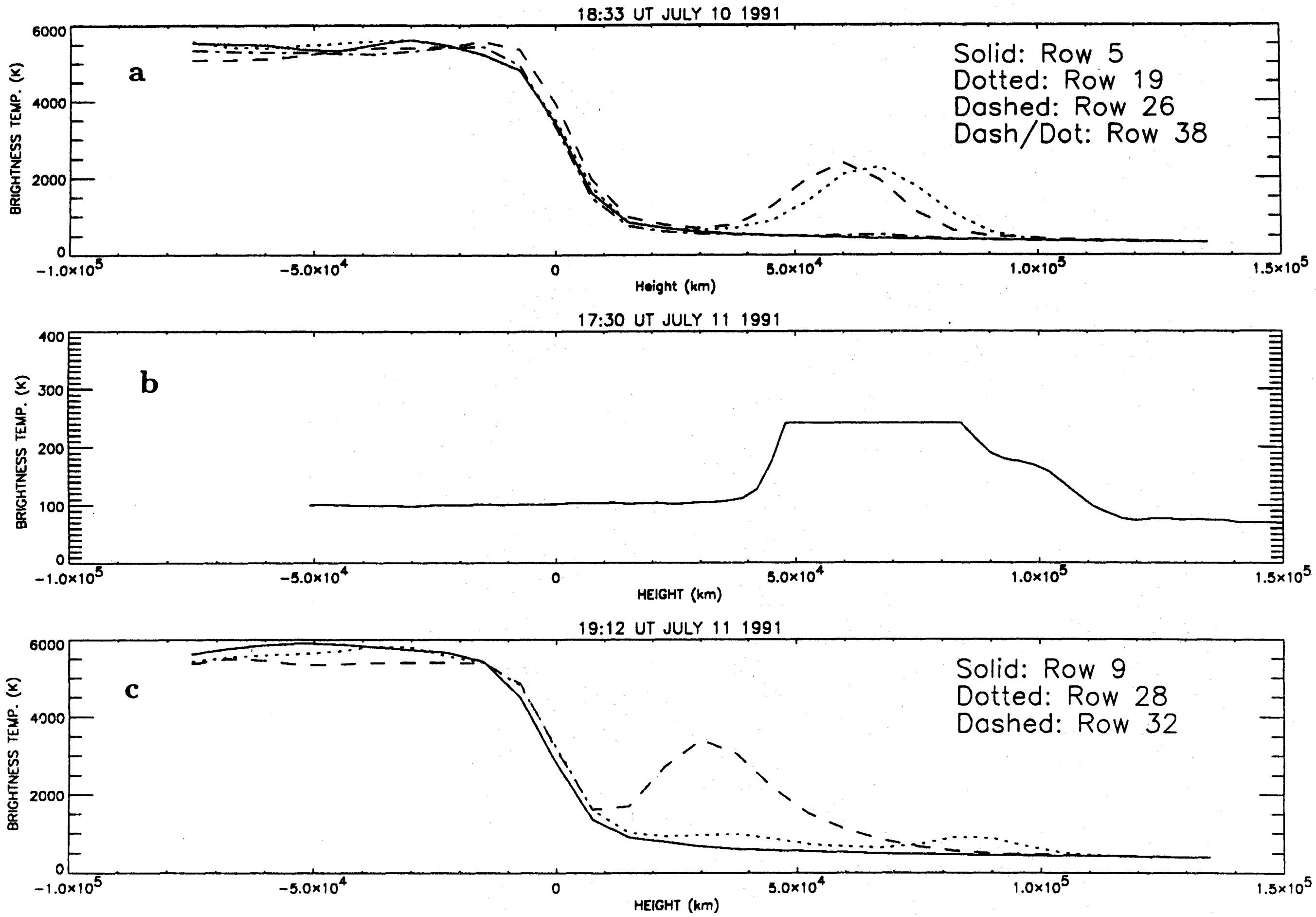

Fig. 2. (a) 1.3 mm brightness as a function of height above the solar limb along columns indicated on Panel (a) in Figure 1. (b) A 1.3 mm scan through the prominence during total solar eclipse at 17:30 UT. The scale of the ordinate is greatly expanded to show the lunar signal (left plateau) and the sky above the prominence (right). The prominence signal itself is far off scale. (c) 1.3 mm brightness along columns indicated on on Panel (d) in Figure 1

$3.2 \times 10^{10}\mathrm{cm}^{-3}$ (Hirayama, 1985), requires a temperature of order 2400 K.

We must consider the orientation of the prominence. The neutral line along which it formed appeared to cross the limb at 45° to the line of sight. Thus, our initial assumption that the path length is equivalent to the observed vertical width is an underestimate. Also, we should consider a filling factor. This would tend to suggest a lower average density than actually exists in the mm emitting plasma. The temperature may be a little higher than anticipated, if these are taken into account.

Further, we must consider the opacty of the prominence. We note that quiescent prominences do not generally appear dark against the solar disc. Even large quiescent filaments are nearly invisible against the solar disc, with a tendancy to show a slight darkening, at 1.3 mm (Lindsey, 1992), but these become clearly dark against the disc at 3 mm, at which the disc radiation is considerably hotter (Hiei *et al.*, 1986). These points suggest prominence temperatures near 5,400 K.

Whilst we cannot unambiguously define the temperature and density, assuming a 33% filling factor, we find that a density of $10^{10}\mathrm{cm}^{-3}$ and a temperature of 6000 K are consistent with our observations of this particular prominence.

It should be clear that more extensive observations of prominences connecting the submillimeter spectrum to the radio can provide a new and valuable perspective on the structure of prominences and filaments. These first observations convince us that a broad class of prominences and filaments are observable throughout this spectral range and that further study will add a new insight to that we have gained from images made in visible chromospheric lines.

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References

Deming, D., Jennings, D. E., Jefferies, J. and Lindsey, C.: 1990, *Solar Interior and Atmosphere* eds. A.N. Cox, W.C. Livingston, M.S. Matthews, 951-3, University of Arizona Press, Tucson

Hiei, et al.: 1986, in *Coronal and Prominence Plasma, NASA CP 2442*, ed A.I. Poland, 109, NASA, Washington DC

Hirayama, T.: 1985, *Solar Phys.* **100**, 413

Lindsey, C.: 1992, in *Proc. IAU Symp. 154 on Infrared Solar Phys.* eds. D. Rabin, C. Lindsey, J. Jefferies, Kluwer, Utrecht, in press

Lindsey, C., Yee, S., Roellig, T.L., Hills, R., Brock, D., Duncan, W., Watt, G., Webster, A. and Jefferies, J.T.: 1990, *Astrophys. J.* **353**, L53

Lindsey, C., Jefferies, J. T., Clark, T. A., Harrison, R. A., Carter, M. K., Watt, G., Becklin, E. E., Roellig, T. L., Braun, D. C., Naylor, D. A. and Tomkins, G. J.: 1992, *Nature* **358**, 308

Priest, E.R.: 1989, *Dynamics and Structure of Quiescent Prominences*, Kluwer Academic Press, Dordrecht

Ruzdjak, V. and Tandberg-Hanssen, E.: 1990, *Dynamics of Quiescent Prominences, Lecture Notes in Physics* **363,** *Proc. IAU Colloq. No. 117*, Springer-Verlag, Berlin

Vernazza, J., Avrett, E.H. and Loeser, R.: 1976, *Astrophys. J.* **30**, 1