INFRARED AND SUBMILLIMETER DIAGNOSTICS OF ACTIVITY AND FLARES

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Abstract. We give a critical review of the observations of solar activity in the IR and sub-mm range, which are quite scarce, except for the Fe I triplet at 1.56 μm and the Mg I emission lines at 12.32 μm. These, however, are mainly intended for solar magnetic field studies rather than physical diagnostics on activity phenomena. We compute the emission in some continuuum windows and in some detectable Paschen and Brackett lines in two extreme flare models, *viz.* a "chromospheric" and a white-light flare model. The utility of the Paschen and Brackett lines as diagnostics of the atmospheric state is questionable since more information can be obtained more easily by observing the higher Balmer lines. On the other hand, observations in various continuum windows can be of high scientific value and efficiency. We also discuss possible coordination with simultaneous visible observations, in order to increase the diagnostic efficiency of a prospective observing run.

Key words: infrared: stars – Sun: activity – Sun: flares

1. Introduction

This paper is organized in 3 different sections: Section 2 contains a synoptic review of papers dealing with IR and sub-mm observations in the field of solar activity; Section 3 discusses the computed emission of flares in various continuum windows and in some detectable Paschen and Brackett lines, for different flare models, and Section 4 presents a possible set of IR and sub-mm observables which, as part of a wider observing program, are suitable for solar activity and flare studies.

2. Review of Existing Observations

No particular attention will be given in the present review to the results obtained for the He I 1.083 μm line, for the Fe I triplet at 1.565 μm and for the Mg I 12.32 μm emission lines. These spectral features have been extensively analyzed in particular sessions of this symposium and the details can be found in other papers of these proceedings. In the following list of works, by no means exhaustive, particular attention was given to the most recent results.

2.1. Sunspots

10 μm (continuum) Turon and Lena (1970) performed at the Kitt Peak National Observatory (KPNO) the first IR observations of sunspots using pinhole photometry.

D. M. Rabin et al. (eds.), Infrared Solar Physics, 113–123.

1.215; 1.670; 1.54; 1.733; 2.086; 2.34 μm (continuum) Albregtsen and Maltby (1981) obtained with refined pinhole-photometry techniques a very important set of data used to build up the umbral "Maltby model" (Maltby *et al.*, 1986). Albregtsen *et al.* (1984) studied the umbral limb-darkening for 22 large sunspots and found a decrease in the umbral/photospheric intensity ratio towards the limb. They confirmed that sunspot intensity varies more or less linearly with the phase of the solar cycle.

1.711 - Mg I, 1.672 - Al I; 1.199, 1.609, 1.538, 2.182 μm - Si I. Van Ballegooijen (1984) used the KPNO FTS to measure these lines in a sunspot umbra and he derived models of the umbra. The high-excitation lines in this set require a hotter model than the low-excitation lines and the continuum and ΔT $\approx$ 460 K at $\tau_{5000} = 3$ between hot and cool components.

850 μm (continuum) At the J.C. Maxwell Telescope (JCMT) in Hawaii, with $\lambda/\Delta\lambda \sim 10^3$, Lindsey *et al.* (1990) found that spots are slightly darker than the quiet Sun, and surrounded by a brighter plage area.

12.32 μm - Mg I. These lines were not seen in umbrae but were detected as fully Zeeman split in penumbrae by Brault and Noyes (1983). They measured $|\mathbf{B}| \sim 900 - 1200$ G in the penumbra. No Evershed outflow was found by Deming *et al.* (1988), who only found Evershed inflow at the limb.

1.5648 μm - Fe I (g = 3.0) and 1.5652 μm - Fe I (g = 1.53). Livingston (1991) found that molecular blends strongly limit the utility of these lines for sunspot studies.

2.2. Faculae

10.5; 18.5; 25.0 μm (continuum). With pinhole scans (10-20″) at the Mauna Kea 2.24 m telescope Lindsey and Heasley (1981) found a contrast $\Delta I/I \leq 0.02$ (much smaller than predicted!). The estimated filling factor was found to be $f \leq 0.1$ (smaller than derived from the Mg-II lines data).

1.627 μm (continuum) Foukal *et al.* (1989, 1990) found a negative contrast using the 58 × 62 InSb–KPNO array with a spectral resolution $\Delta\lambda = 40$ Å.

2.3. Supergranular structure

1.17 μm; 1.64 μm (continuum); 1.7108 μm - Mg I. Worden (1975) measured a ΔT ranging from 50 K at 1.64 μm (formed at the deepest observable layer) to 500 K at 1.7108 μm (formed at the low chromosphere).

850 μm (continuum). Lindsey *et al.* (1990) and Lindsey and Jefferies (1991) at the JCMT, with resolution $\lambda/\Delta\lambda \sim 10^3$, found that the network is approximately correlated with Ca II structures. Assuming a mean value for the brightness temperature T_b of 5400 K, they found for the supergranular network 5050 K $< T_b <$ 5750 K.

2.4. Prominences

10 - 20 μm. For high hydrogen lines (observed with the KPNO FTS), Zirker (1985) found results consistent with known scenarios. No Stark wings were measured on these IR lines.

2.5. Emerging Flux Regions

12.32 μm - Mg I. Zirin and Popp (1990) measured a line-center contrast $I/I_{\rm quiet} \sim 1.13$, implying $|\mathbf{B}| \sim 700$ G, and a total line contrast $[\int I\, d\lambda]/[\int I\, d\lambda]_{\rm quiet} \leq 3$.

2.6. Plages

0.4 - 0.8 - 1.2 mm. With a pinhole bolometer, 3′ resolution, Beckman and Clark (1973) found evidence that T_b rises with height.

850 μm (continuum). At the JCMT Lindsey *et al.* (1990) determined $\Delta T_b \sim 1100$ K.

12.32 μm - Mg I. Brault and Noyes (1983) for the first time resolved the Zeeman splitting in plages.
Deming et al. (1988) measured a mean value for $|\mathbf{B}|$ of 400 G.
Zirin and Popp (1990) found a line-center contrast $I/I_{\rm quiet} \sim 1.06$–$1.12$. For an old plage the total line contrast $[\int I\, d\lambda]_{\rm plage}/[\int I\, d\lambda]_{\rm quiet} = 1$ and $|\mathbf{B}| \sim 200$ to 400 G; for a young plage they found a contrast of 3.0 and $300 < |\mathbf{B}| < 800$ G.

1.5648 and 1.5652 μm - Fe I. Rabin *et al.* (1991) determined $|\mathbf{B}| \sim 800$–1600 G using the new two-dimensional near-IR magnetometer equipped with the KPNO 58×62 InSb array with 2″ resolution.
Livingston (1991) found $|\mathbf{B}| \sim 1000$–2000 G using the main McMath with 4″ resolution.

2.7. Flares

4.1 mm (73 GHz). Akabane *et al.* (1973) determined that the time profile of the H_α and mm-bursts approximately coincide; this behaviour was not found for the cm bursts.

3.3 mm (90 GHz). Shimabukuro (1970, 1972) found that gradual and impulsive bursts were well correlated (in shape and time) with soft X-ray (SXR) bursts (2-12 Å). They could not explain this correlation with the values of emission measure and electron temperature derived from SXR bursts.
Kaufmann *et al.* (1986) and Costa and Kaufmann (1986) showed that very fast pulses (~ 60 ms) at mm wavelengths were well correlated with hard X-rays (HXR) bursts. A spectral flattening was found at mm wavelengths. Their interpretation was that the mm-wavelength emission was due to synchrotron radiation and the HXR emission to inverse Compton scattering. This interpretation was rejected by McClements and Brown (1986), who suggested a compact source (~ 350 km) with $|\mathbf{B}| \sim 1.4$ to 2.0 kG, and $N_e \sim 10^{11}$ cm^{-3}

and $T_e \sim 5 \times 10^8$ K. Their interpretation was that the mm-wavelength emission was due to gyrosynchrotron radiation and the HXR emission to bremsstrahlung. The need for higher spatial and temporal resolution at mm wavelengths was stressed.

3.5 mm (86 GHz). Kundu *et al.* (1992) reported interesting observations obtained with the BIMA interferometer (1-2″ resolution) during the 1991 Solar Maximum campaign. They found two phases in mm-burst emission: a) a non-thermal impulsive phase correlated with HXR (25-100 kev) bursts, which is believed to prove the existence of a MeV electron beam (but sometimes the mm-spike has a 5-10 s delay with respect to the HXR spike); b) a thermal gradual phase correlated with the SXR behaviour. Other possible scenarios are also presented. Evidence for pre-flare heating at mm wavelengths is found.

20 and 350 μm (continuum). The first pioneering attempts to detect IR emission from flares were due to Hudson (1975) at the 152 cm IR telescope on Mt. Lemmon. Negative results were obtained, probably due to the lack of strong activity and to instrumental limitations including pinhole rastering.

12.32 μm - Mg I. At the KPNO–FTS, Deming *et al.* (1990) performed the first observations of a flare, with spatial and temporal resolutions of $\sim 5''$ and 2 minutes respectively. The 2 ribbon flare 3B/X5.7 of October 29, 1989 was observed 25 minutes after the HXR peak but simultaneously with the SXR maximum emission. The continuum intensity contrast $\Delta I/I_{\rm quiet} = 0.07 \pm 0.03$, was explained with a temperature enhancement $\Delta T \sim 300$ K at h $\sim$ 400 km corresponding to $\tau_{5000} \sim 10^{-2}$. They found that $|\mathbf{B}|$(penumbra) $\sim$ 2.1 kG and $|\mathbf{B}|$(umbra) $\sim |\mathbf{B}|$(penumbra) $-$ 0.2 kG. No spatial or temporal variations in $|\mathbf{B}|$ were detected. Variations of $\gamma = \arctan(\mathbf{B}_{||}/\mathbf{B})$ probably reflect relative intensity variations of the σ/π Zeeman components, possibly related to magnetic reconnection processes, *viz.* to the formation of post-flare loops.

We would like to point out the importance, and the significance for the understanding of flares, of the results obtained by Deming *et al.* (1990) and by Kundu *et al.* (1992), which were made possible by new high-quality instrumentation. The latter paper, particularly, has been discussed during this meeting and we refer to that presentation for further details.

We would like to comment on these results:

- The diagnostic capabilities of IR and sub-mm observations for solar activity and flare studies have been almost totally neglected, mainly due to the lack of suitable, *dedicated* panoramic instruments.
- The observations of active phenomena in the 1.56 μm Fe I and 12.32 μm Mg I lines are only a by-product of observations intended to study the magnetic fields.
- IR observations can now be used effectively to study active phenomena, since they have attained reached the quality of observations in the visible (2-D arrays, *etc.*).

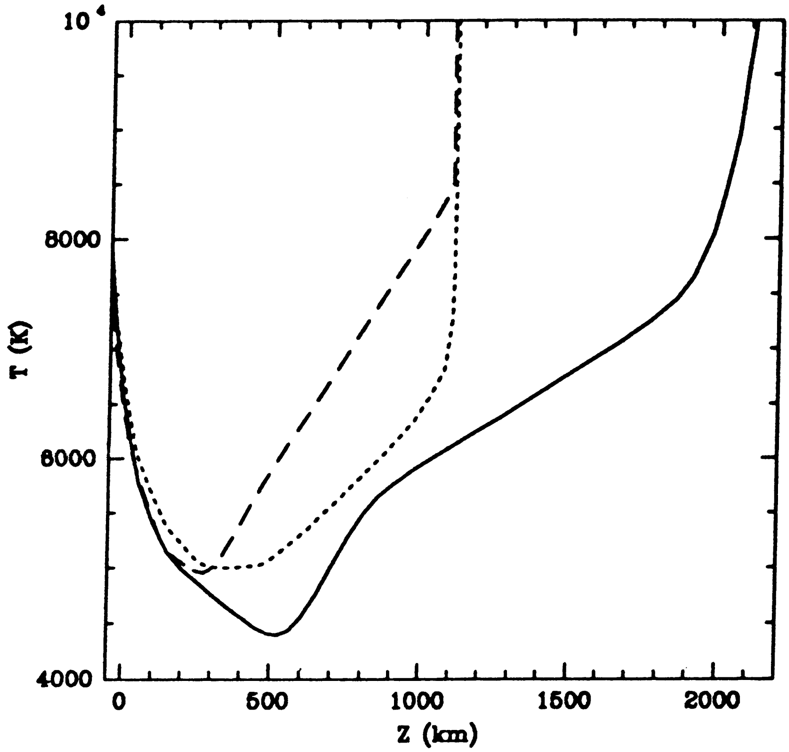

Fig. 1. Electron temperature as a function of height for several atmospheric models. *Full line:* Quiet Sun (Avrett, 1985); *dashed line:* Intense "chromospheric" flare model FL2 (Machado *et al.*, 1980); *dotted line:* White-light flare model FLA (Mauas *et al.*, 1990).

3. Diagnostic Capability of Some IR and Sub-mm Spectral Features

To see which IR and sub-mm observations are better suited to study activity phenomena, we evaluate the sensitivity of the different observables to changes in atmospheric models. We concentrate our attention on flare studies, since their contrast is larger (and hence more easily detectable) than for other active phenomena, even if their unpredictability may represent a real observing complication. Moreover, a wide variety of sufficiently reliable flare models (both semi-empirical and theoretical) is available.

We note the following continuum windows:

- 1.17 μm because optical depth unity at that wavelength corresponds to optical depth unity at 0.5 μm;
- 1.627 μm, the minimum of the continuum absorption coefficient;
- 2.2 μm. The "classical" continuum IR window. At this wavelength a "negative" flare was observed in the case of the flare star AD Leo (Byrne, 1989 and references therein). The absorption dip was measured concurrently with the flare emission in the visible and radio, and so far no reasonable explanation

has been offered. We believe that this kind of observation should be repeated for other flare stars, in particular the Sun.

- The 3.8, 5.0 and 10.0 μm regions which offer clean continuum windows observable with ground-based optical techniques;
- The 30, 50, 100, and 200 μm regions, not reachable from the ground but important potentially for indicating the position of the flare transition region (TR) and corona;
- The 350, 850, 1000, and 3000 μm continuum windows, which can be reached from the ground and with a spatial resolution of several minutes of arc.

We considered 4 detectable hydrogen lines in the near IR (where panoramic detectors and narrow–band filters or spectrometers may be available): P_β at 1.2818 μm, P_γ at 1.0938 μm, Br_α at 4.0512 μm and Br_γ at 2.1655 μm. The computations have been performed with the NLTE code PANDORA (Vernazza, Avrett and Loeser 1973, 1981). All canonical mechanisms for the continuum opacity have been considered (including H^-, H_2^+, and Rayleigh and Thompson scattering). We also included the opacity due to the 1.7×10^7 weak atomic and molecular lines compiled by Kurucz (1985), as explained by Avrett, Machado, and Kurucz (1986).
For the present exploratory work we considered three atmospheric models:

- the modified VAL-C model (Avrett, 1985) for the quiet Sun;
- an intense flare model FL2 (Machado *et al.*, 1980) capable of reproducing many chromospheric and transition region features;
- a white-light flare model FLA (Mauas *et al.*, 1990) with smaller chromospheric temperatures but a hotter photosphere.

The height distribution of the electron temperature for the three models is given in Figure 1.

3.1. The Sensitivity of the IR Continuum Windows to Flare Models

The computed intensities in the different continuum windows for the three models are listed in Table I. The physical significance of the results of our numerical simulations, quoted in Table I, can be summarized as follows:

- The 1 to 5 μm range is formed approximately around optical depth unity at 0.5 μm,
- No negative-flare signature around 2.2 μm is noted (this fact adds weoght to arguments for repeating the IR continuum observations of stellar flares),
- Continuum observations in the 1 to 10 μm range can give valuable information on the physical processes occurring in a white-light flare (WLF). Since, the only opacity source is H^-_{ff} (the contribution of the Brackett continuum is negligible, $\sim$ 2 to 8%), the change in the observed emission during the WLF should originate in the photosphere.
- 350 and 850 μm continuum radiation originates at the low chromosphere in the quiet Sun, and at the transition region in a flare. Thus a very high contrast (easy to measure) would be observed at these wavelengths during a flare.

TABLE I

IR continuum window sensitivity to flare models. QS is the quiet sun model (Avrett, 1985), FL2 is the intense chromospheric flare model (Machado *et al.*, 1980), FLA is the white-light flare model (Mauas *et al.*, 1990); h and T are the height and the temperature of the layer where most of the emergent radiation originates. C = I/I_{QS} is the computed emission contrast.

	QS		FL 2			FLA		
$\lambda(\mu m)$	h	T	h	T	C	h	T	C
1.17	0	6250	0	6420	1.1	0	6700	1.1
1.63	-20	6980	-25	6910	1.0	-25	7200	1.1
2.2	0	6520	0	6420	1.0	0	6700	1.1
3.8	50	5790	50	5840	1.0	50	6010	1.1
5.	50	5790	50	5840	1.1	50	6010	1.1
10.	150	5150	150	5140	1.2	150	5370	1.1
30.	300	4770	1025	8120	1.6	275	5030	1.1
50.	350	4660	1075	8360	1.9	1110	9840	1.1
100.	400	4560	1098	8487	2.1	1110	9840	1.3
200.	490	4410	1100	8500	2.8	1110	9840	1.7
350.	560	4430	1102	22000	3.9	1110	9840	2.1
850.	980	5900	1103	35000	5.9	1112	17300	3.1
1000.	980	5900	1103	35000	6.5	1112	17300	3.4
3000.	1580	6900	1105	150000	13.6	1114	43400	6.3

3.2. The Sensitivity of Some Hydrogen Lines to Flare Models

In Figure 2 we show the computed profiles of P_β, P_γ, Br_α and Br_γ for the atmospheric models plotted in Figure 1. In Table II we list the computed contrasts, with respect to the quiet Sun, of IR and Balmer lines for both flare models at different spectral resolutions.

We see that even with an infinite resolution, the contrast at the line center for the IR lines is smaller than for the Balmer lines. Note that the broad-band line contrast, corresponding to the flare model FLA, is mainly due to the continuum emission enhancement caused by the temperature increase in photospheric layers, rather than to real line emission. Furthermore, since all of these lines are not formed in local thermodynamic equilibrium, the Paschen and Brackett lines (corresponding to transitions between higher levels) are harder to interpret than the Balmer lines. If we also consider the experimental simplicity and the huge variety of observing tools available for the Balmer lines (in the visible range) in comparison with the IR lines, we conclude that, at present, the IR hydrogen lines do not help for a better understanding of solar activity.

4. Conclusions

The key ingredient for a better understanding of the basic mechanisms determining solar activity is the careful measurement of the velocity and the magnetic fields

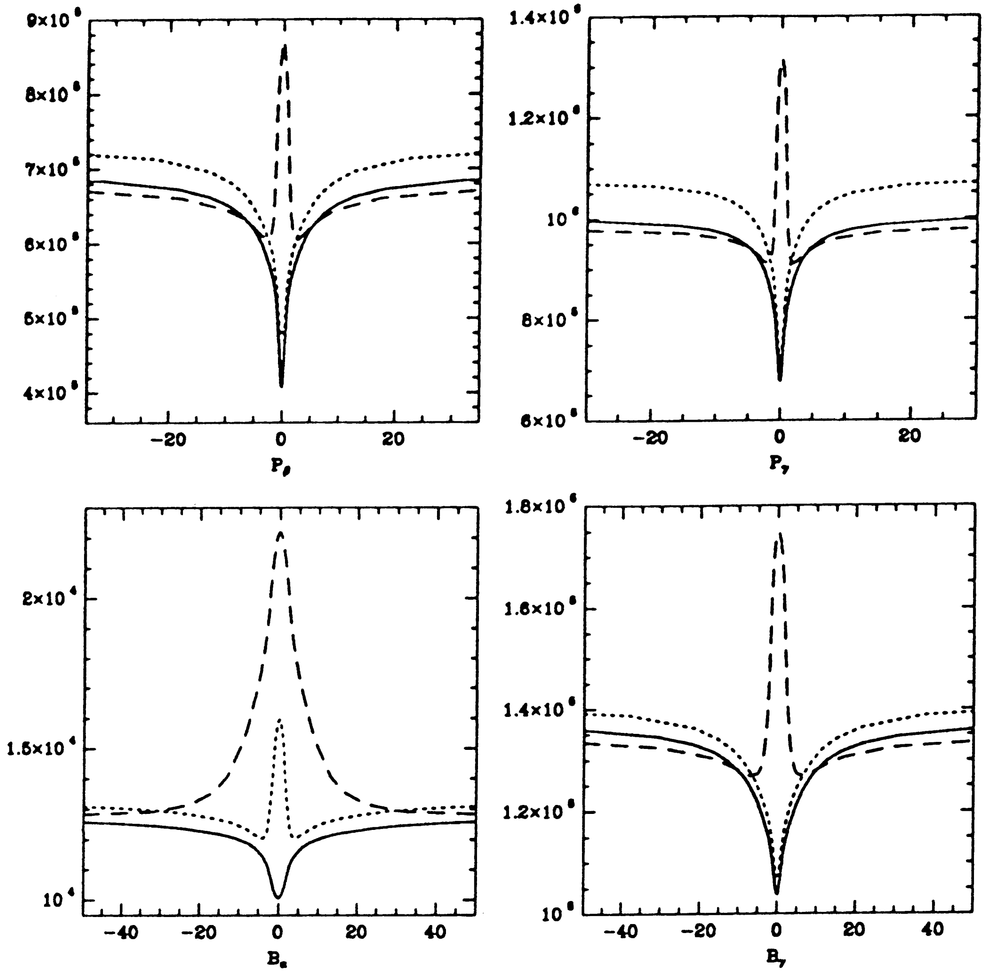

Fig. 2. Computed profiles of several hydrogen lines for different atmospheric models. *Full line:* Quiet Sun (Avrett, 1985); *dashed line:* Intense "chromospheric" flare model FL2 (Machado *et al.*, 1980); *dotted line:* White-light flare model FLA (Mauas *et al.*, 1990).

and their interactions at high spatial and temporal resolution, at different heights in the atmosphere (*e.g.* Falciani, 1988; Falchi *et al.*, 1991). Moreover, an efficient and well-planned set of photospheric and chromospheric observations has the goal of determining the spectral signatures correponding to the different physical processes (particle acceleration and subsequent bombardment, EUV and X-ray irradiation, thermal conduction, *etc.*). For example, very recent results (Falchi *et al.*, 1992; Cauzzi *et al.*, 1992;) indicate the presence of a strong velocity field on some metallic lines one minute before the start of an HXR burst. In a very small area ($\approx 3''$) a blue shift of the order of 15 km s^{-1} lasts for one minute. The rapid evolution of this blue-shifted Doppler component in a small spatial patch offers a new, evolving,

TABLE II
Hydrogen line sensitivity to flare models. FL2 is the intense chromospheric flare model (Machado *et al.*, 1980), FLA is the white-light flare model (Mauas *et al.*, 1990); C_0 is the contrast I/I_{QS} computed in the line center and C_{20}, C_{40} are the contrasts integrated over ±10 and ±20 Å from line center.

	FL2			FLA		
	C_0	C_{20}	C_{40}	C_0	C_{20}	C_{40}
P_β	2.1	1.1	1.0	1.2	1.1	1.1
P_γ	2.4	1.1	1.0	1.0	1.1	1.1
Br_α	2.2	1.6	1.3	1.6	1.1	1.1
Br_γ	1.7	1.1	1.1	1.1	1.0	1.0
H_α	8.9	-	-	7.2	-	-
H_β	9.6	-	-	6.5	-	-
H_γ	7.0	-	-	3.8	-	-
H_δ	5.4	-	-	2.4	-	-

scenario for the development of the chromospheric flare.

We would like to conclude by proposing a coordinated observing program in which IR observations may represent an important diagnostic tool. We characterize this program by different spectral ranges to help to define possible future collaborations between different research groups.

VISIBLE RANGE

One– and two–dimensional spectroscopy in several spectral lines would allow us to estimate, not only the thermal structure of the atmosphere, but also the velocity and magnetic fields at different heights. Resolutions of $\Delta t \sim 2$ to 20 s and $\lambda/\Delta\lambda \sim 10^5$ would be required.

IR LINES

Observations of the 1.56 μm - Fe I and 12.32 μm - Mg I lines would allow us to measure magnetic fields with greater precision than can be obtained in the visible lines. The 1.083 μm line is a very important diagnostic of the excitation of He I.

IR CONTINUUM

Observations at 1.17, 1.627, 2.2, 3.8 and 10 μm may allow us to estimate the maximum penetration of the flare and to distinguish between photospheric and purely chromospheric white-light flares.

Observations in the first three continuum windows may represent optimum use of the new NSO/KPNO 128×128 IR array, which may reach resolutions of the order of $\Delta x, \Delta y \sim 1''$, $\Delta t \sim 2$ to 5 s, $\lambda/\Delta\lambda \sim 10^3$.

Observations in the 350 and 850 μm continuum windows can be used to monitor low intensity events, due to the high contrast expected at these wavelenghts. With the presently-available observational resources, resolutions of the order of Δx, Δy $\sim 6''$, $\lambda/\Delta\lambda \sim 10^3$, Δt $\sim$ 0.5 s per pixel (in raster mode) can soon be reached.

MILLIMETER WAVELENGTH RANGE

The recent results obtained with instruments with high spatial resolution (*e.g.*, JCMT, BIMA, Caltech IR facility) are the best and most convincing proofs that observations at this spectral range can supply evidence of the propagation of very high energy electrons.

MICROWAVE RANGE

High-time-resolution ($\leq$ 1 s) dynamic spectral observations can supply valuable information on the non-thermal processes acting in the observed region

It is quite obvious that, to complete this ideal data set, space-born information on SXR, HXR, γ-rays and in-situ particle detection should be available.

We believe that at this stage of our understanding of solar activity, very little can be learned without a coordinated set of observations in the different spectral ranges. With this objective in mind, it would be necessary to solve a large set of problems, for example, coordination of the pointing and orientation of the field of view of the different instruments involved.

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