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Near infrared observations of the solar atmosphere

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Abstract. Due to the availability of the advanced two dimensional array detectors for detecting the near infrared (IR) wavelength, it has become possible to study new aspects of solar atmosphere during the recent times. The main aspects of solar physics in near IR are: (1) The Zeeman sensitivity, which is the ratio of Zeeman splitting and Doppler width, is directly proportional to the wavelength. Therefore, compared to the visible window infrared is favourable for making accurate measurements of magnetic field. (2) The opacity for solar radiation reaches a minimum value at 1.6 micron. The study of the continuum radiation at this wavelength makes it possible to probe the solar atmosphere deeper than the visible photosphere. Also, the magnetic field at this layer can be measured by selecting the Zeeman sensitive lines near 1.6 micron. (3) Since the continuum and many other spectral lines are formed essentially in local thermodynamic equilibrium, the infrared spectrum provides a complementary view of the inhomogenities in solar atmosphere to that observed in short wavelengths. I shall review these aspects with special emphasis for future observations during the next solar maximum.

1. Introduction

Even though the Infrared (IR) observations of the sun dates back to 1800 AD, when William Herschel discovered "*invisible solar radiation redward of what our eyes can see*", the full potential usage of this window in solar physics is just beginning. It is mainly due to the recent advancement of the detector and other associated technologies. Also, many major facilities are being planned for future observations of the sun at near IR. Hence, the next decade will witness a major contribution to our knowledge of the solar atmosphere from this wavelength window. I shall concentrate on the ground based observations in this review, since this is the only mode with which the solar observations can be carried out for a longer span of time. Also in ground based instruments specialized observations can be planned in a short notice, which is not possible in the case of space based instrumentation.

2. Atmospheric window

The earth's atmosphere does not allow all the IR radiation to reach its surface. The molecules such as water and CO_2 in the atmosphere, have dipole moments which give them a plethora of vibrational and rotational modes whose, frequency corresponds to wavelength between 1 and 100 microns. Therefore, the infrared photons reaching the atmosphere have a strong likelihood of exciting a suitable transition and being absorbed. The superposition of these lines, in particular due to the rotational frequencies of water, make the atmosphere totally opaque in the far infrared. Only in the mid and near IR, there are transparent bands, which are referred to as atmospheric windows. Table 1 summarizes their characteristics from observation point of view. Since the atmospheric transparency mainly depends on the water vapour content of the earth's atmosphere, a dry place, preferably where its fluctuation is less, is preferred for IR observations.

Table 1.

Wavelength range (micron)	Central wavelength (micron)	Filter disignation	Atmospheric transparency	Atmospheric background
1.1-1.4	1.25	J	Good	Low
1.5-1.8	1.65	H	Good	Low
2.0-2.4	2.20	K	Good	Low
3.0-4.0	3.50	L	Fair	Moderate
4.6-5.0	4.80	M	Low	High
7.5-14.4	10.0	N	Fair	Very High

3. Magnetic field measurements

The main advantage of the measurements of the magnetic field in infrared compared to visible lines is that the splitting of the spectral lines are higher in the former case for a given magnetic field strength due to their higher Zeeman sensitivity as it increases linearly with the wavelength. In visible wavelength, the splitting of the spectral lines are due to Zeeman effect, for typical field strength of 1500G, is comparable of less than the Doppler line width, hence the lines are not completely split. This introduces an error in measuring the magnetic field in a location having the spatially unresolved mixed polarities, due to the fact that depending on the magnetic polarity the resultant profile leads to cancellation and changes in the shape of the final stokes V profile. This is more important in the case of studying the active regions as the mixed polarity regions are often encountered there (Zirin and Wang, 1993). When the lines are completely split, as in case of IR wavelengths, the true field is measured (Solanki, 1991).

Another aspect of measuring the magnetic field in near IR is that it contains the Zeeman sensitive lines with widely different properties, particularly with different formation height. Table 2 gives few examples. Additionally the line forming conditions of Ti I 2.2310 micron is such that it may be best suited for studying the umbral magnetic field. Details of IR magnetometry are given in Solanki (1994) and Ruedi et al. (1995) and Solanki (1991).

Table 2.

Zeeman Sensitive line (microns)	g-factor	Formation height	Reference
FeI 1.5648	3	Lowest observable layer	Solanki et al., 1992
Mg I 12.32	1	Upper Photosphere	Damings et al., 1994
He I 1.0830		Upper Chromosphere	Solanki et al., 1994

4. Opacity minimum

The second important aspect of the solar observation in near IR is due to the fact that at this wavelength, it is possible to observe the layers deeper than the visible photosphere (τ_{500nm}~1). It is because of the fact that the principal source of continuum opacity in the IR is primarily free-free absorption by H^- (negative hydrogen ion) as pointed out by Chandrashekhar in 1946, with some contribution due to H free-free absorption. The opacity is simple and in local thermodynamic equilibrium with electron density. At short wavelengths (shortward of 1.65 micron) bound-free contribution must be considered, which is zero at dissociation threshold of 1.65 micron. Therefore, the opacity is minimum at 1.65 micron. This implies that at this wavelength it is possible to observe the layers deeper by about 35 to 40 km from the visible photosphere, where most of the interesting physical processes are going on due to the fact that the energy balance of the sun changes rapidly at these layers from convective to radiative transport.

5. HeI 10830 Å

The HeI 10830 Å line is formed in the upper chromosphere and coronal transition region at a height near 2000 km above $\tau_{500nm} = 1$ region of the solar atmosphere. The line originates basically due to the photoionization of the species from coronal X-ray and UV radiation and recombination process. The local conditions also contribute to the line formation, which are not well understood so far. However, many coronal features, which can be observed only in X-ray or UV are seen in the 10830 spectroheliograms. The similarity between the X-ray and 10830 images are striking. Therefore, this line can be used for ground based coronal studies effectively. The HeI 10830 Å can also be effectively used for measuring the magnetic field of the upper chromosphere (Ruedi; et al. 1995; Penn and Kuhn, 1995).

6. Molecules

The discovery of the existence of pockets of molecules in the solar atmosphere has shown that the chromosphere is far from an homogeneous structure. One such example is CO molecule, whose $\Delta v=2$ overtone band lies near 2.3 micron and $\Delta v=1$ fundamental band lies near 4.66 micron. The vibration-rotation lines are thermalized by low energy collisions with atomic hydrogen and consequently form close to the local thermodynamic equilibrium. Although the individual oscillator strengths are small, the large abundance of CO in the cooler layers causes the absorption core to raise at high altitudes, especially for viewing angles close to the limb. The multiplicity of CO transitions provides a high degree of observational redundancy and a wide range of formation height with which to probe the temperature profile. Therefore, these molecules are key diagnostics of the temperature-pressure stratification of the solar outer photosphere.

7. Solar flares

The solar flares are the most glamorous topic of solar physics. IR technique has a lot to contribute in this field. One direct application is of course measuring the magnetic field (Penn et al. 1995). The 1.6 micron continuum band can also be effectively used to study the subphotospheric conditions of the active region and its relation to flare production.

8. Eclipse observations

The Total Solar Eclipse gives an unique opportunity to study the solar corona and the outer chromosphere from the ground. Apart from the usual green coronal line, recently there have been suggestions to use some near IR lines for coronal density diagnostics. For example, at a temperature of 1.8×10^6 FeXIII line at 1.0747, 1.0798 and 0.3388 micron will have more flux than green Fe line. For a typical coronal loop interaction with electron density of 10^8 cm^{-3} 1.0747/1.0798 ~ 1, which increases to 2.5 to 3 for temperatures of 2×10^6 K. On the other hand 3388/1.0747 ratio is very sensitive to electron density. 1.0747 line is highly sensitive to polarization. A study of its polarization property as a function of height would give the information of electron collision.

Eclipse observations of the distribution of CO emission at 4.66 micron, above the solar limb are very important from the point of view of studying the temperature inhomogeneity of solar atmosphere. During 10 May 1994 solar eclipse observations have been carried out with McMath-Pierce Telescope (Clark et al., 1995) at Kitt Peak. The limb profiles of CO line intensity show that it changes from absorption to emission and this extends beyond the limit of height which depends linearly upon the line strength. This result places important constraints on models which incorporate a cool component into a structured solar atmosphere.

9. Solar oscillation studies

In near IR wavelengths, some important studies of solar oscillations can be addressed. For example, the problem of dynamics of small scale magnetic flux tubes can be addressed in a most direct fashion by using near IR line due to their higher Zeeman sensitivity. Muglach et al. (1995) have shown that at FeI 1.5648 micron the dominant oscillatory signature in velocity data is due to 5 minute oscillations, in addition 5 minute and 9-10 minute oscillations of magnetic field strength are also observed. In 4.66 micron CO band and 1.0830 micron HeI line also several important studies of solar oscillations are carried out (Solanki et al., 1996).

10. Existing facilities

At present solar IR observations are initiated at various observatories. The most important instrumentation in IR observations is carried out at National Solar Observatory, Tucson. The instrument consists of a near IR camera, which is placed at the exit port of the spectrograph at the McMath-Pierce Telescope. This is called near the infrared magnetograph - I or NIM - I

(Rabin, 1994), which is a spectrometer based magnetograph. The advanced version of this magnetograph, which has a two dimensional imaging capability, will have a Queensgate Fabry-Perot tunable filter and will observe the magnetic field in the imaging mode. The NSO/NASA video filtergraph/magnetograph is currently completed and making the 10830 spectroheliograms (Jones and Harvey, 1995). The vector magnetometry using 12 micron Mg I emission line is being developed at NSO by NASA/GSFC (Deming et al. 1994). The German Vacuum Tower Telescope at Tenerife, uses an 256×256 Amber AE4256 camera system, with liquid nitrogen cooled InSb detector system sensitive from 1 to 5 micron range (Soltau, 1995). The 10830 spectroheliograms are also obtained at Norikura Solar Observatory, Japan (Suematsu et al., 1995). It should be mentioned here that many of the instruments mentioned here are in their early stages of fabrication. When fully operational they aim to observe the sun during its peak activity in AD 2000.

11. Future plans

Besides these instruments, which are meant to be used with the existing telescopes, major instruments are being planned for near IR solar observations in future. The most important being CLEAR (Coronagraph and Low Emissivity Astronomical Reflector) being planned at NSO. This is a 4-meter class solar telescope aimed at observing both the solar disk and the solar corona at all wavelengths from 0.3 to 35 micron. This telescope would use a single mirror which is superpolished and has low thermal emissivity in IR (Beckers, 1995). Besides this LEST, proposed upgradation of solar telescope at Kitt Peak McMath-Pierce Solar telescope to 4 meter aperture and THEMES have very important instrumentation plans to observe the sun in IR wavelengths.

12. Consideration for instrumentation

Angular Resolution: The magnetic flux tubes in the plage and network areas are sub-arcsecond structures, with characteristic diameters of ~200 km (Steiner, 1993). To resolve the single flux tubes, the resolution of less than 1 arcsecond is required. It has been seen during the solar cycle 22 that the locations of the super active region which are complex in magnetic structure are the site for large flares (Zirin and Wang, 1993). To study such regions, resolutions of the order of an arcsecond is required. In order to achieve, these resolutions at longer wavelengths, large aperture telescopes, equipped with adaptive optics, are required. Observations at 1.6 micron region offer compromising constraints. At this wavelength, for 1.5 meter telescope the diffraction limit is below 0.3 arcsecond. The adoptive optics needed to approach the diffractive limit are expected to be less difficult than at visible wavelengths (Roddier and Graves, 1993).

Photon flux: The ground based polarimetry is done by rapidly modulating between the complementary polarization states (eg: Stokes I±V) in order to minimize the signal to noise degradation due to seeing. The intrinsic magnetic field strength and direction can be obtained only at $\lambda/\Delta\lambda \sim 10^5$. These requirements, along with the need for higher angular resolution implies that the photon flux is an important consideration for the imaging polarimetry.

Let us take an example in case of studying the coronal magnetic field by using the FeXIII lines at 1.0750 and 1.0790 microns, which is situated near the HeI 1.0830 micron line. This line has a g-factor of 1.5. Let us consider a rather bright coronal loop of surface brightness 50×10^{-6} per 0.1nm pass band of solar disk brightness. By using the formula (Koutchmy and Smart, 1989) to estimate the Zeeman amplitude, we find 2×10^{8} are needed for 10 Gauss field with S/N=10, assuming the spatial integration of 3.3x3.3 arcsecond square, and overall efficiency of polarization analysis 0.1. This implies that for a intergration time of 50 seconds the needed telescope size is 1 meter aperture.

Polarized Signal: In visible wavelength region the low level of linear polarization is produced (of the order of 10^{-3}–10^{-4}) due to incomplete Zeeman splitting. At 1.6 micron, the prevalence of strong splitting means that Stokes Q and U are comparable in strength with Stokes V. On the other hand the infrared lines are generally weaker, reducing the amplitude of all Stokes components. Since the components are comparably strong, linear-to circular crosstalk cannot be ignored as it often can be in case of visible light.

Detectors: With the stringent constraints mentioned above, it is apparent that good detectors with better signal to noise must be employed for the study. The standard detector for 0.3-1.1 micron is CCD, which has high quantum efficiency and is readily available in 2048x2048 format. The IR arrays operating at 1.6 micron range are made with HgCdTe, InSb and PtSi. They are available in formats ranging 64x64 to 512x512. Many IR arrays are designed to run at video or higher rates, which satisfies the need for rapid polarization modulation. The best suited for solar problem seems to be InSb arrays, which can be used in the spectral range of 0.6 microns to 5.5 microns (Fowler, 1995).

Telescope mirror: Special considerations must be made for telescope mirrors when used for IR studies. The primary mirror coating together with the atmosphere are the most important contributors to the IR emissivity. A cooled mirror is most preferred. Also, in this wavelength range, it is not possible to use the windows, hence the vacuum or He filled telescopes are ruled out. Therefore for image quality, other methods such as active and adaptive optics must be explored. This is specially important in the case of the large aperture telescopes.

13. Conclusions

In conclusion, we have tried to point out many interesting problems of solar physics which can be addressed with the use of near IR window for observations. The investigation of solar atmosphere in near IR also poses new and exciting instrumentation in the coming years. In the context of "Solar Physics in India" it may be pointed out that: (1) There is sufficient expertise in the field of IR instrumentation in the country, in particular at Physical Research Laboratory. (2) However, if the efforts in this area are not started early, we may not be able to take part in the real excitement of the field.

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