High-Resolution Thermal Infrared Imaging of the Sun: A Pipe Dream?

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Abstract. I discuss the desired characteristics of an instrument to study the Sun in the 3–20 μm thermal infrared. I show that even the largest apertures under consideration for a next generation "Advanced Solar Telescope" fall short of the capabilities needed at the long wavelengths. I conclude that the design of AST should not be driven by access to the thermal infrared. Instead the IR would be better served by a special-purpose instrument; even a simple—perhaps temporary—modification of an existing or planned nighttime telescope.

1. Introduction

One of the central mysteries of solar physics—and indeed of stellar astronomy—is the process by which kinetic energy of the turbulent convection zone is transferred across dozens of scale heights to the outer atmosphere, deposited there as heat, boosting temperatures to $10^4$–$10^6$ K. Decades of detailed reconnaissance of the solar surface and upper atmosphere have pointed to the central role of the spatially complex magnetic field, although there are thought to be heating processes—particularly in the largely field-free cell interiors—that are purely dynamical in nature. In parallel, solar modellers have moved away from thinking in terms of a "layered" atmosphere, to the more natural view of "structures." Growing awareness of the dynamic complexity of the coronal regions, motivated by the stunning images from SOHO EIT and now TRACE, has spawned new descriptive metaphors: for example, "the coronal junkyard" (attributed to Helen Mason); and my contribution, "battle in a rubberband factory."

1.1. The magnetic transition zone

Fig. 1 is a cartoon of the modern view. Within the new paradigm, one can identify a crucial region: the "magnetic transition zone" (MTZ) separating the high-$\beta$ plasma of the deep photosphere, where the embedded magnetic field is carried about by the gas flows; and the low-$\beta$ regions of the outer atmosphere, where it is the field that guides and controls the gas dynamics. The MTZ is of great interest because—as is the nature of "boundaries"—profound changes occur in the character of the atmosphere: thin, filamented, sparsely-distributed flux tubes below; broad, pervasive canopy, and tangled mess of coronal loops, above.
Figure 1. Cartoon of "magnetic transition zone." Height "0" is at $\tau_{5000\,\AA} = 1$.

Perhaps coincidentally, the MTZ also corresponds to the pressure range in the outer atmosphere where acoustic waves radiating from the chaotic convective cells in the deep photosphere steepen and form shocks (as in the Carlsson-Stein [1997] 1-D radiation-hydro simulations): the MTZ not only is a critical interface between plasma-domination and magnetic-control, but it also defines a zone where the gas dynamics (away from strong fields) evolves from small-amplitude nearly-adiabatic disturbances, to strongly dissipative shock waves.

Remote sensing of physical conditions in the MTZ is a key observational goal for those who wish to understand the propagation of mechanical energy through the solar outer atmosphere, and the complexification of the magnetic "flora" as one proceeds from the deep photosphere out to the corona.

1.2. Far-UV space/time diagrams

One way to view the MTZ is through ultraviolet spectral imaging, in moderate excitation species (the 1300–1700 Å continuum, or first ions such as Si II and Fe II). This can be done at ~2'' resolution with SOHO SUMER. Fig. 2 illustrates an example, from an observation in May 1997. SUMER slit No. 2 (300'' in length, 1'' in width), oriented N/S, was placed +700'' west of the central meridian ($\mu \sim 0.7$). Solar rotation carried the surface westward across it at a rate of 1 slit-width per 10 minutes, building up a drift-scan of transient and persistent surface features over time.

The intensity map (left panel) is based on the $\lambda 1321$ continuum; the Doppler velocities (right panel) are from a sharp Si II chromospheric emission at $\lambda 1309$. Each exposure was 60 s: the 350 consecutive frames spanned nearly six hours.
According to classical layered models (Vernazza, Avrett & Loeser 1981), the $\lambda$1321 continuum forms on the high side of the initial temperature rise out of the $T_{\text{min}}$ region. The Si II $\lambda$1309 emission would form somewhat above that level.

The intensity image is peppered with short vertical streaks representing transient brightenings, and horizontally-elongated features produced by long-lived bright structures. The middle frame is a spatial map of persistent features obtained by filtering the space/time diagram to suppress the short-lived intensity fluctuations. The depiction is reversed with respect to normal convention, with W to the left and E to the right (to maintain the same orientation as the space/time diagram).

The velocity map is coded such that dark areas indicate strong line-of-sight redshifts ($v_{\text{los}} > +2$ km s$^{-1}$), the lighter shaded areas are strong blueshifts ($v_{\text{los}} < -2$ km s$^{-1}$), while the white background encompasses the smaller positive and negative velocities in the distribution. The velocity zero is based on a global average over the space-time diagram, after a systematic trend in the spatial dimension was removed.

The upper panels illustrate histograms of brightness temperatures derived from the calibrated intensities (left panel) and line-of-sight velocities (right panel).
panel). While the intensities in the image span more than a decade, the temperature histogram is nearly symmetric, with only a weak tail on the hot side; and the rms is only about 80 K. (Note: owing to NLTE effects, the λ1321 temperatures very likely are lower than the true kinetic temperatures in the continuum-forming gas.) In the ultraviolet, in the Wien limit, a great deal of intensity contrast can be produced by even a rather bland temperature field. The temperature histogram undoubtedly is dominated by oscillations, which at this level should be nearly adiabatic: the huge intensity swings are an insignificant energy drain, and don’t affect the thermodynamics of the waves.

I constructed a mask to isolate the bright regions, above a selected threshold, which are persistent in time (as in the middle panel). The thick light-shaded curve in the temperature histogram depicts the population of the mostly network elements. These features are systematically 100–200 K warmer than the dominant temperature of the map, and occupy less than 10% of the scene.

I then applied the network bright-point mask to the velocity map. The light-shaded curve in the velocity panel shows the resulting histogram. The network points display a broad velocity distribution like the rest of the scene, but systematically skewed blueward (by about 1 km s⁻¹). The physical significance of the shift is uncertain.

What is clear, is that we can determine properties of the flow fields near the base of the MTZ through ultraviolet spectral imaging. However, the intensities in the ultraviolet are comparatively low (about five orders of magnitude less than visible intensities, when measured in instrumentally meaningful units of photons per Doppler width), and the contemporary small-aperture solar instruments in space are capable of only modest spatial (1″–2″) and temporal (~1 min) resolution. An instrumental remedy—large-aperture orbiting UV solar telescope—likely would be a billion dollar undertaking. Furthermore, the thermal emissivity in the far-UV is strongly biased towards hotter temperatures, and NLTE scattering effects are endemic. Thus, it is advantageous to look elsewhere in the spectrum to find more suitable diagnostics of plasma conditions and dynamics at the base of the MTZ.

1.3. Infrared thermal maps

There have been a number of previous discussions of the importance of the 4.7 μm fundamental vibration-rotation bands of carbon monoxide for inferring physical properties of the gas high in the solar photosphere (e.g., Ayres & Rabin 1996, and references therein). The lines are numerous and cover a wide range of excitation; they are strong—mostly because CO is abundant where conditions favor its formation; and collisional quenching of the excited states is rapid, so NLTE effects are unimportant. Altogether, CO is the diagnostic of choice for cool material high in the solar photosphere; occupying perhaps a unique position in that regard.

Fig. 3 illustrates a space/time sequence of CO brightness temperatures and velocities, based on three strong absorptions: 2–1 R6, 3–2 R14, and 4–2 R23. The observations were obtained with the McMath-Pierce telescope and IR spectrometer, using a fixed slit at disk center, in 1996 May 10 under conditions of good seeing. The diffraction limit of the 1.5 m telescope is about 0.″8. The N/S length of the slit is only about 1/8-th that of the SUMER observations, and the
frame cadence was about 20 times higher, yielding a (disk-storage-limited) sequence of only 25 min (still satisfactory for establishing temperature and velocity distributions for the typical 3–5 min waves at those altitudes).

Owing to the denser sampling of the IR sequence, I have depicted the velocities as an overlaid contour map: solid curves indicate redshifts; dashed curves, blueshifts. One clearly sees the alternating patches of Doppler shifts that signal the presence of 5-min p-mode “wavepackets.” The temperature pattern loosely follows the compressions and rarefactions that accompany the velocity disturbances; namely, the compressional phase of the wave (velocity turning point following the maximum redshift) often shows an enhanced brightness temperature, while the other turning point (trailing the maximum blueshift) displays cooler temperatures expected for the near-adiabatic expansion phase.

The upper panels of Fig. 3 depict temperature (left) and velocity (right) histograms derived from the IR space/time diagram. The CO temperature centroid is a few hundred degrees cooler than its far-UV continuum counterpart, but very likely is a better gauge of the true kinetic temperatures where the strong CO lines become optically thick. Curiously enough, the rms width of the temperature distribution is similar to that of the far-UV continuum (although, again, the role of NLTE effects in the latter have not been evaluated). The CO velocity histogram, however, is much narrower than that of the far-UV Si II emission; by almost a factor of ten. This suggests that the Si II feature forms much higher up than the CO bands, at lower pressures where the wave amplitudes have grown considerably (at least in velocity).

Figure 3. Space/time diagram for 4.7 μm CO lines.
As with the far-UV maps, I devised a mask for the CO space/time diagram; although now to isolate the cooler areas of the pattern. The selected population ($T < 4100$ K) is illustrated by the light-shaded curve in the temperature histogram; the corresponding velocity distribution is depicted in the right panel. Unlike the situation in Fig. 2, here we find that the “cool-patch” velocity distribution is somewhat narrower than the global histogram, and shows no evidence for any large systematic shifts. If the cooler areas are associated with the $p$-modes, one would expect a narrower line-of-sight velocity distribution, centered at $v = 0$, since the maximum rarefaction phase of the oscillation occurs at the velocity turning point.

On the other hand, if the cooler CO areas are produced by overshooting convective granules (Han Uitenbroek’s 1999, this volume), one would expect to find systematic blueshifts associated with the cool regions at this level (disk center view)—with lifetimes comparable to those of granules ($\sim$ tens of minutes)—in order to produce the even cooler gas seen several scale heights above (in extreme limb views, and off-limb). Instead, the dominant velocity (and temperature) patterns are short-lived and oscillatory in nature.

The rectangular insets in the temperature and velocity panels illustrate a resampling of the rapid-cadence time sequence to the $\sim 1$ min resolution of the far-UV maps. Although clearly the IR side is deficient in both spatial and temporal coverage, the temperature and velocity maps display the same “streaky” appearance as their far-UV counterparts; showing the importance of these types of measurements for evaluating the dynamical state at the lower boundary of the MTZ. Of course, the major limitation at present is the diffraction limit of even the largest available IR-capable solar telescope, the McMath-Pierce. We can’t know, for example, whether there are finer-scale cold points below the current $\sim 1''$ horizon, whose properties might lead to a ready explanation for the extreme-limb darkening and off-limb emissions of the strong CO lines, without having to invoke a large volume of cool material in a pervasive “COnosphere” (see Ayres & Rabin 1996).

1.4. Translimb emissions of CO

I mentioned the off-limb emissions of CO in the previous discussion; they play a key role in understanding the thermal organization of the “belly” of the MTZ. Any cold material ($T < 4000$ K) at high altitudes—interlaced with the magnetically complex canopy fields—could be of fundamental importance owing to its large resistivity compared with the highly conducting gas inside the ionized flux tubes (J. Chae 1999, this volume). Fig.4 depicts an example of the best measurements of the CO translimb region obtained to date. The bottom panel depicts the coaddition of five frames selected from a sequence of 1000 by a limb-sharpness criterion; taken under calm conditions with good seeing at the North limb. Each of the “bumps” represents the frequency-resolved profile of the translimb emission of an individual CO line. (The image was divided by the average spectrum at $\mu \sim 0.2$ in order to normalize the intensities and suppress telluric absorptions.) In the upper panel, the dots depict frequency-resolved measurements of the off-limb extensions relative to the continuum; the thin solid curve at the top of the panel shows a high-resolution (FTS) relative intensity tracing of the disk-center absorption spectrum. At each frequency, the
translimb intensities roll-off smoothly on a scale of 1"–2" representing the blurring effects of diffraction and scattering. The “subresolution” off-limb extensions are measured as differential displacements. On the other hand, higher angular resolving power would suppress any influence of the instrumental profile on the apparent off-limb extensions; this is particularly important for the weaker lines that provide key information concerning the “loading” of cool material along the long tangential sightline above the continuum limb (see Ayres & Rabin 1996).

2. Discussion

The foregoing examples should make it clear that with the existing McMath-Pierce infrared facility, we can obtain comparable or better spatial resolution at the base of the crucial MTZ than contemporary far-UV instruments, with much higher sensitivity. We could do even better from the ground, by going to apertures larger than the present 1.5 m maximum, at a tiny fraction of the cost (and risk) of a major space mission. How much aperture is needed? To answer that question, we must consider in more detail the two key issues: spatial resolution and sensitivity.
2.1. Infrared detectors and ambient thermal background

Before addressing these issues, I'll digress briefly to mention detectors and thermal background. In the ultraviolet and visible, camera technology is relatively mature, and high-quantum efficiency devices are readily available in increasingly large formats. In the thermal infrared, on the other hand, detector technology is much less advanced. Furthermore, even with the most sensitive devices, one must contend with the high external thermal background (sky plus telescope plus spectrometer, if the latter is not cooled) which contributes photon noise but no signal. While it is possible to approach the photon counting limit in the ultraviolet and visible, the accessible S/N in the mid-infrared—for the same photon flux—always will be much lower, if only because of the ubiquitous thermal background.

2.2. Spatial resolution

The angular resolving power of a telescope is

\[ \delta \theta \sim 0.2 \left( \frac{\lambda_{\mu m}}{D_m} \right), \]

where \( \lambda_{\mu m} \) is the observing wavelength in micrometers, and \( D_m \) is the primary mirror diameter in meters. For example, the planned Solar-B space-borne telescope is designed to achieve 0.2 resolution in the visible with a 50 cm mirror. Right away, you can see that to obtain comparable resolution at even the short end of the thermal IR (say, at the key 4.7 \( \mu m \) CO bands) requires a 5 m telescope. To image down to the horizontal photon mean-free path (\( \sim H_p \sim 0.1 \) for structures that are \( \tau \sim 1 \) thick in their vertical dimension) adds another factor of two in aperture; i.e., 10 m for the CO bands.

2.3. Sensitivity

The specific intensity (photons per Doppler width) in the thermal infrared is down by about an order of magnitude compared with the peak of the radiant energy distribution near 4000 \( \AA \). That is not as bad as the far-UV case mentioned previously, but qualitatively points to the need for a larger collecting area in the IR to duplicate the sensitivity of an optical solar telescope of given diameter. The question is: how much?

Putting aside detector performance issues for the moment, let’s assume that we have perfect photon-counting cameras for both the visible and 5 \( \mu m \) regions. We then can estimate the ratio of collecting areas which will yield the same sensitivity, given a specific remote sensing application. For the sake of argument, consider the most basic physical measurement one might wish to obtain, namely the detection of a given temperature difference \( \Delta T \) on the solar surface with a specific S/N and angular resolution in an integration time \( t \).

Consider a power-law approximation to the thermal emissivity (Planck function)

\[ B(T) \sim b_\lambda \left( \frac{T}{5000 \ K} \right)^{\sigma_\lambda}. \]

If we take a small temperature range near 5000 K (a typical photospheric value), the coefficients are as follows.
The $b_\lambda$ values, above, are in units of photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ per 1 km s$^{-1}$ Doppler width. (Note: the visible and infrared photon emissivities at 5000 K are closer than the observed 0.5 $\mu$m and 5 $\mu$m intensities, because $\tau_\nu \sim 1$ occurs at a higher temperature in the visible than in the mid-IR.) The table emphasizes the fact that at the shorter wavelengths the thermal emissivity becomes a progressively steeper function of temperature, whereas in the mid-infrared the Planck function is essentially linear in $T$.

Now, for a specified temperature contrast $\Delta T / T$, we obtain the associated relative intensity contrast

$$\frac{\Delta B}{B} \sim a \left( \frac{\Delta T}{T} \right).$$

(3)

The corresponding signal is

$$\Delta \text{counts} \sim a \ B \ \ A_{\text{eff}} \ \delta \omega \ \Delta v_D \ t \left( \frac{\Delta T}{T} \right),$$

(4)

where $A_{\text{eff}}$ is the effective area of the instrument, $(\pi/4) D^2 \epsilon_\lambda$, the geometrical collecting area times the downstream efficiency (coatings plus instrument plus detector); $\delta \omega$ is the solid angle subtended by the camera pixels; and $\Delta v_D$ is the equivalent Doppler bandpass of the spectral measurement. The noise (counting statistics, ignoring any backgrounds) is

$$\sigma_B \sim (B \ A_{\text{eff}} \ \delta \omega \ \Delta v_D \ t)^{1/2},$$

(5)

i.e., the square root of the total counts. The S/N is the ratio of the former to the latter

$$S/N \sim a \ (B \ A_{\text{eff}} \ \delta \omega \ \Delta v_D \ t)^{1/2} \left( \frac{\Delta T}{T} \right).$$

(6)

To measure the same $\Delta T$ with the same S/N in the same $t$ with the same angular resolution $\delta \omega$ (for spectral diagnostics of similar Doppler width) requires

$$\left( \frac{A_5}{A_{0.5}} \right)^2 \left( \frac{b_{0.5}}{b_5} \right)^2 \sim 5 \times 10^1!$$

(7)

So, even if the system efficiency $\epsilon_\lambda$ is the same at 0.5 $\mu$m and 5 $\mu$m (and it is likely to be much less at the longer wavelength if only because of the thermal background), one still requires a $\sim 7\times$ larger diameter telescope in the IR to measure temperature contrasts with the same sensitivity as in the visible. One is forced to conclude that both resolution and sensitivity call for a $\sim 10\times$ increase in telescope aperture for thermal IR work. Another way of looking at
it: the current McMath-Pierce telescope performs as well at 4.7 μm as a 15 cm instrument would in the visible!

The astute reader might be wondering at this point: why bother with the thermal infrared at all; can’t we just work in the visible? The answer is that the only places in the visible where one can “see” as high an altitude as probed by the CO bands are the cores and inner wings of strong resonance lines, where NLTE effects and partial coherent scattering obscure the true sizes and temperatures of the radiating structures. The LTE CO lines, on the other hand, are much cleaner diagnostics of the physical conditions, but the price you pay is having to build a big telescope.

2.4. Is AST a possible solution?

Could the proposed Advanced Solar Telescope do the job? The facility presently under consideration is of 3 m class. With adaptive optics, such an instrument could provide—during periods of good seeing—resolution in the visible down to the 0″/1 considered essential for breaking new ground in understanding small-scale solar phenomena. That performance could be achieved out to ~1.5 μm, where important magnetically-sensitive lines fall (such as used by Doug Rabin’s Near Infrared Magnetograph). With the large aperture, there also would be plenty of light to record fast-changing phenomena via narrow-band spectral imaging ( Keller 1999, these proceedings). Out at 4.7 μm, however, a 3 m solar telescope would represent a much more modest improvement over the existing McMath-Pierce, achieving a diffraction-limited spatial resolution of only 0″/4; still far away from the small scales where a great deal of crucial action might be occurring. While an “open” AST would yield better performance in the thermal infrared than the best existing solar IR telescope, it will not provide the order of magnitude improvement that likely is needed to boost our understanding to the next level.

2.5. Design considerations

The previous arguments point to a solar infrared telescope of aperture 5–10 m. Considering how difficult (and expensive!) it will be to design and build a properly-functioning 3 m AST, the concept of a much larger telescope—dedicated to the niche application of IR thermal imaging—sounds like a pipe dream. Perhaps. But, there are several considerations that I have not mentioned yet, which might make such a concept practical.

First, there already are (or soon will be) lots of telescopes around the world of 8–10 m aperture, albeit in the hands of the darksiders. Might it be possible to retrofit one of those nighttime facilities to permit it to be used profitably during the day? After all, the JCMT has been used to observe the Sun in the sub-mm band, with special precautions to protect the radio dish. I have not looked into the technical aspects (politics aside), but I believe that heating of the primary mirror (and potential damage to the coating) would be minimal (most of the ~1 kW m⁻² would be reflected, not absorbed), but clearly a specially designed secondary and heat dump would have to be provided to protect against the intense fluxes at the (typically fast) focus. Retrofitting a current nighttime telescope would be challenging (perhaps impossible politically), but the option is worth considering for a future facility for which solar access could be built.
in from the beginning. I have in mind a hypothetical nighttime IR-optimized
telescope (not yet proposed) with an open, off-axis design that would lend itself
naturally to the solar option (as in Jacques Beckers’ original proposal for the
CLEAR telescope).

A second important point is that while a sensitive high-resolution IR tele-
scope (solar or otherwise) must be large, it need not be as expensive to build as
a conventional optical facility. In particular, the tolerances for mirror curvature
and surface roughness are a factor of 10 looser at 5 μm than in the visible, and
that applies to the whole optical train as well. One can get away with a much
lighter mirror, perhaps metal rather than glass, which in turn permits a lighter
(therefore cheaper) support structure. Perhaps one could do away with the con-
ventional telescope tube by employing an articulated beam feed that would follow
the gross motion of the solar image (from, say, a 10 m lightweight segmented
mirror supported in a simple polar mount, or more flexible alt-az configuration),
carrying a heat shield to dump most of the solar beam, with an agile
secondary to correct for short-term image motion and more slowly changing
mirror aberrations. At the conclusion of observing, the arm could be retracted
and stowed, allowing a low-profile enclosure (perhaps a clamshell like that used
on the Dutch Open Telescope described by Rob Rutten 1999, these proceedings).
The driving motivation for building such a telescope would have to be nighttime
IR astronomy, but solar could piggyback with relatively modest additional cost.

A final possibility, that has been discussed for almost a decade now, is the
“Big Mac” proposed by Bill Livingston and Bob Noyes. Their concept was
to replace the 1.5 m Main mirror in the McMath-Pierce with a much larger
aperture: up to 4 m diameter would fit in the existing tunnel. However, that
design would cause enormous heating in the tunnel, and surely would lead to
much worse internal seeing than already exists. I offer a modification; which is,
I warn, not yet as well thought out as the original Big Mac design.

I would replace the heliostat by an off-axis main focussing mirror, with a fast
enough f-ratio to form an image near the entrance to the tunnel, or somewhat
inside. I believe there is room at the top of the McMath-Pierce for up to a 6 m
heliostat, so a primary of that class probably could be accommodated. I would
put a heat dump at the (short) focus to divert most of the light harmlessly
away from the tunnel, passing only whatever few arcminutes of the beam the
instruments downstream could profitably use. Suitable optics in the tunnel
would magnify the image and transfer it to the Main spectograph (or FTS)
station at an appropriate plate scale.

One innovation is that the surface roughness of the main mirror could be
controlled to be fully reflective at 5 μm, but mostly “dull” in the visible so that
much of the incident optical light would be diffusely scattered, while the desired
IR would be specularly reflected (I have seen such a design for a spacecraft
instrument to measure ~ 100 μm solar radiation). Heat loads at the beam
dump would be reduced, but possible deleterious influences on the scattering
wings of the instrumental spatial profile (e.g., for translimb work) would have
to be evaluated carefully.

A final point to consider is that initially one might experiment with only
a partially-filled aperture, in particular a linear mirror, say five or six 1 × 1 m
segments carried perpendicular to the tunnel axis. Such a configuration would
yield high spatial resolution in one dimension (East/West, in this case), but
only modest resolution in the other. Such a design is well-suited for long-slit
imaging of spatial structure on the disk, and for exploring the translimb zone at
high resolution. Heat loads would be reduced by a factor of nearly five, and the
supporting structure could be much simpler than for a monolithic 6 m. Costs
certainly would be reduced, as well, perhaps to the level where such a project
might be accomplished for only a modest investment. The main advantage of
utilizing the McMath-Pierce is, of course, the good (i.e., dry) IR site, existing
infrastructure, and full complement of high-performance infrared instruments.

3. Conclusions

I have three main conclusions: (1) it is astrophysically worthwhile to observe,
at the very least, the 5 μm region of the solar spectrum—longer wavelengths
still are pretty much unexplored, and indeed are awaiting development of so-
lar IR telescopes of higher angular resolution and sensitivity; (2) the apertures
required to achieve high spatial resolution and good sensitivity in the thermal
infrared are so much larger than presently under consideration for the AST, that
it does not make sense to shackle the design of the latter with the requirement
to pass radiation longward of ~ 3 μm; and (3) the mid-infrared is much less
constrained—from a telescope design point of view—than the visible, so it is
worthwhile to consider piggybacking solar IR capability on existing or planned
nighttime facilities, or retrofitting the McMath-Pierce with specially-designed
IR optics to take advantage of its existing complement of instruments. Failure
to seize such opportunities, I fear, will cause infrared solar physics to languish;
and a unique tool will be lost to explore physical conditions at the base of the
vital—but enigmatic—magnetic transition zone.

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References


Group Discussion

Chae : What line did you use for the production of the first Doppler shift map?
Have you examined the possible effect of line blending?
Ayres : I used the SiII 1309 line, but did not examine the line blending.