

The Case for Spectroscopic Observations of Very Hot (5-10 MK) Plasma

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The large majority of important solar phenomena involve a sudden conversion of magnetic energy into other forms (heat, bulk flows, energetic particles). Just how this conversion works is not, however, well understood. The basic concept of magnetic reconnection is familiar, but many fundamental aspects remain a mystery. If we are ever to understand coronal heating, flares, coronal mass ejections, jets, etc., we must understand how magnetic fields allow stresses to build to large values and then suddenly break and violently rearrange. This is the essence of much of solar physics.

To make real progress, we must observe the plasma as the energy release is happening and immediately afterward. This has yet to be done in a truly meaningful way. Most existing coronal observations are at temperatures of 1-2 MK, far below the expected temperatures of the energized plasma. We observe the plasma only after it has cooled, when vital information about the energy release process has been lost. In fact, the situation is much worse. Mostly what we see is entirely different plasma that has been evaporated from the chromosphere and dominates the coronal emission. We have few direct signatures of the actual energy conversion process.

Theory tells us that magnetic reconnection can take several forms, involving laminar outflow jets, plasmoids ejected along current sheets, or turbulent dynamics. In some situations (e.g., CMEs), some of these features may be large enough to be spatially resolved, but in general they are too small. Even with outstanding spatial resolution, we are forced to contend with disparate plasmas overlapping along the optically thin line-of-sight. The only way to obtain quantitative information about unresolved and overlapping plasmas is with spectroscopy. Doppler shifts and line profile shapes tell us about the distribution of velocities, while multiple emission lines reveal the distribution of temperatures. Densities can be measured with line ratios. High cadence imaging is very powerful when observing well resolved uniform plasmas, but many solar phenomena are fundamentally complex and require a spectroscopic approach. Ideally, one would have a spectrometer and imager flying together and complementing each other.

The 5-10 MK temperature regime is largely unexplored in solar physics. Some spectroscopic observations of very hot plasmas do exist, and they hint at the value of such observations, but the data are very limited. This is truly one of the last great discovery spaces in our field. Dedicated high temperature spectroscopy would allow us to seriously diagnose the details of magnetic energy conversion for the very first time. It would give us new insights into the inner workings of CMEs, nanoflares, and a host of other phenomena.

High-temperature observations have of course been performed in hard X-rays. However, these observations are of continuum Bremsstrahlung emission, and any information on flows is limited to proper motions at coarse spatial resolution. Spectral lines are needed for detailed

studies of magnetic energy conversion, and these can be found in three different wavelength regimes: 1000 Å, 100 Å, and 10 Å. Each has its strengths and weakness, and further study will be required to determine which is optimal. Several factors need to be considered.

It is desirable to observe multiple emission lines that fully sample the temperature space. It is also desirable that these lines be unblended with cooler lines, which can significantly complicate the interpretation. Shorter wavelengths are preferable in this respect.

In order to use the shapes of line profiles to infer unresolved flows, it is necessary to have good spectral resolution. This favors longer wavelengths. It is not difficult to achieve $\lambda/\Delta\lambda = 30,000$ at 1000 Å, which corresponds to 10 km s⁻¹ spectral pixels. Doppler shifts (average velocities) can be measured to a much higher precision.

Very hot emission is expected to be quite faint for three reasons: densities are relatively low at the time the energy release occurs (evaporated material is much denser); very hot plasma cools quickly and is short lived; non-equilibrium ionization can reduce the population of highly ionized states. It is therefore desirable to have a sensitive instrument that targets intrinsically strong lines. This generally favors longer wavelengths.

The attached chart summarizes the relative strengths and weaknesses of the three wavelength regimes that can be used for high-temperature spectroscopy. Example instrument concepts are indicated along with their observing technique (grazing or normal incidence spectrometer, microcalorimeter). The wavelengths and relative intensities of several Fe ions with formation temperatures ranging from 7-11 MK are provided for each of the color coded wavelength regimes. These are the intrinsic emissivities, independent of the emission measure or observing instrument. The lines near 10 Å are roughly an order of magnitude fainter than those near 100 and 1000 Å.

In summary, the 5-10 MK temperature regime is a largely unexplored discovery space, precisely where magnetic energy conversion is occurring. Spectroscopy in this regime can be expected to provide breakthroughs in understanding the conversion process and therefore in explaining many important solar phenomena. As with any fundamentally new observation, we can also anticipate unforeseen surprises. Some might argue that there is a risk, since very hot emission is expected to be faint. However, flying a "safe" mission that makes incremental progress in a well established area is not the way to significantly advance solar physics. We need something scientifically very exciting, and high-temperature spectroscopy is it!

References are available upon request.

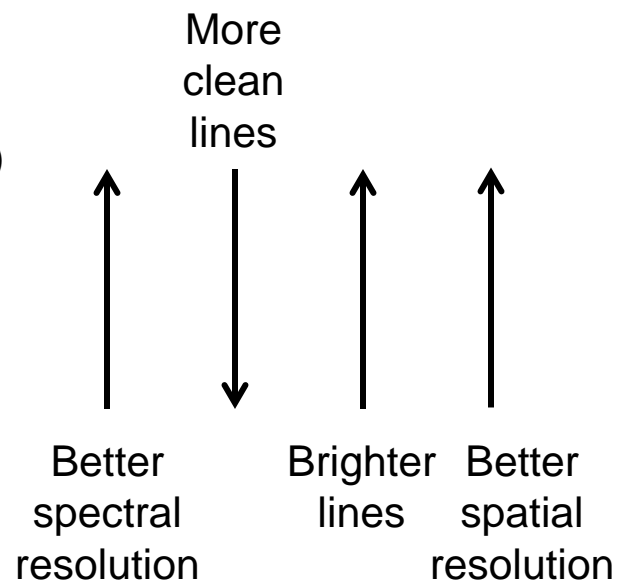
Comparative Wavelength Regions

~ 1000 Å (EUVST/LEMUR, normal inc spec, R = 30,000)

~ 100 Å (EUNIS, normal inc spec, R = 10,000)

~ 10 Å (MaGIX, grazing inc spec, R = 1000)
(Solaris-X, microcal, R = 1000)

$$R = \lambda/\Delta\lambda = 10,000 \leftarrow \rightarrow 30 \text{ km/s}$$



Fe XVIII
logT = 6.85

974.86 46
93.93 39
14.20 6

Fe XIX
logT = 6.95

1118.05 47
108.35 50
13.52 5

Fe XX
logT = 7.00

121.84 46
12.82 4

Fe XXI
logT = 7.05

1354.06 121
128.75 99
12.28 9