The Case for Comprehensive Spectroscopic Measurements of the Sun: Understanding Solar Flares and Coronal Heating

Jeffrey W. Brosius (Catholic University of America at NASA/GSFC)
Peter R. Young, James A. Klimchuk, Terry A. Kucera, & Adrian N. Daw (NASA/GSFC)

Synopsis: We discuss spectroscopic capabilities needed to resolve two important unresolved questions in solar physics, namely, "What heats the solar corona?" and "What causes the sudden, rapid release of energy that produces flares?" Spectroscopic capabilities needed to answer these questions include: (1) high spectral resolution, to enable measurement of unblended profiles of numerous emission lines; (2) high sensitivity with a wide dynamic range, to enable detection of faint line emission as well as weak wing components; (3) comprehensive temperature coverage, observing lines formed at log T separated by 0.1 or 0.2 dex between at least 20,000 K and 20 MK; (4) an absolute wavelength scale, to enable Doppler velocity measurements accurate to within 1 km/s or better; (5) simultaneous measurements over spatial area comparable in size to active regions ($4' \times 4'$); (6) spatial resolution sufficient to resolve loop strands and the immediate vicinities of reconnection sites ($< 1''$); (7) cadence short enough to monitor evolution of the solar atmosphere during periods of most rapid change (< 1 s).

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Two important unresolved questions in solar physics are: (1) What heats the solar corona? (2) What causes the sudden, rapid release of energy that produces flares? Comprehensive spectroscopic measurements are essential to answer these questions.

The solar atmosphere along any given line of sight emits optically thin radiation from plasma over widely ranging temperatures. Some radiation becomes optically thick low in the atmosphere, but optically thin radiation from the outer atmosphere is present no matter what solar feature is observed, from flares and quiescent active regions to quiet Sun areas and coronal holes. The range of temperature is larger during flares than it is in quiet areas or coronal holes, but in all cases it exceeds an order of magnitude. For example, the temperature of the upper chromosphere is around 20,000 K ($\log T = 4.3$); during flares, plasma is heated to tens of million Kelvin ($\log T \gtrsim 7.3$), so the range of temperatures observed along a line of sight can exceed three orders of magnitude. In quiescent active regions the "typical" coronal temperature is around 3 MK, while in coronal holes and quiet Sun areas it is 1 - 2 MK; in these cases the range of temperatures is close to two orders of magnitude.

To understand what initiates the release of flare energy, how that energy is transported throughout the flaring region, and how the atmosphere evolves in response, spectroscopic measurements are required over the entire range of temperature that occurs during flares. Spectroscopy of flaring regions needs to begin well before flare onset so that any and all behavior leading up to rapid energy release can be observed. Ideally, we need to be able to detect unblended line emission from plasma at 10 - 20 MK or hotter, as well as unblended line emission at temperatures all the way down to and including that of the chromosphere. Observations of the 10 - 20 MK plasma represent our best hope of directly probing the site(s) of flare energy release. Of course, chromospheric evaporation is also typically observed at such high temperatures, but evaporation is a secondary effect, produced when the chromosphere is heated due to a combination of thermal conduction from the reconnection site, nonthermal particles accelerated in or near the reconnection site, and possibly waves.

Sufficient spectral resolution is needed so any line identified in the observed spectra can be uniquely, unambiguously ascribed to a particular line (or self-blend) of a particular ion. Line profiles need to be sufficiently well resolved, and the spectral intensity measurements need to be sufficiently sensitive, to enable the detection of faint blue- and/or redshifted components in a line's wings. Further, well resolved line profiles would enable nonthermal motions to be determined via broadenings in excess of the line's thermal width. (When thinking in terms of actual observations, the instrumental profile would need to be narrow and well defined.) Further still, an absolute wavelength scale needs to be reliably defined such that line-of-sight motions could be established to within 1 km/s or better. These motions need to be reliably measured simultaneously for not only the line profile centroid, but also for any and all components that are Doppler shifted into the wings. This becomes important during flares when "stationary" components due to radiation emitted from hot, dense loops filled with evaporated plasma become extremely bright. The filled loops are much brighter than (1) the material expelled by reconnection jets, which may be seen in both blueshifts and redshifts near the reconnection site; (2) simultaneously upflowing and downflowing material during explosive chromospheric evaporation, and upflowing material during gentle chromospheric evaporation; and (3) downflows due to cooling, condensing, falling material. Emission lines over the entire temperature (wavelength) range all need to be observed simultaneously, so Doppler shifts and nonthermal broadening can be measured simultaneously over the entire temperature range. To ensure comprehensive temperature coverage, it would be ideal to observe emission lines separated by 0.1 or 0.2 dex in log T between about 20,000 K and at least 20 MK. Some blending of solar emission lines is inevitable, but with continuing advances in both atomic physics databases and in spectroscopic resolution, this type of comprehensive temperature coverage should be achievable.

In addition to comprehensive temperature coverage, wide spatial coverage is essential. To understand how the atmosphere responds throughout the region in which energy is released and transported, comprehensive temperature coverage must be acquired simultaneously over a portion of the solar disk as least as large as an active region (typically $4' \times 4'$). Spatial resolution should be sufficient ($< 1''$) to resolve small-scale features such as loop strands and the vicinities of reconnection sites. Flares evolve rapidly particularly during the impulsive phase, so cadences shorter than 1 s would be required. Timing differences between the brightenings and flows of evaporated chromospheric material provide insight into the dominant mechanism(s) of energy deposition into the chromosphere (thermal conduction, nonthermal particles, waves).

The capabilities such as those described above would be further valuable for addressing the nanoflare model of coronal heating. This model posits that numerous tiny, unresolved impulsive heating events (likely, but not necessarily, due to reconnection among twisted, tangled sub-strand magnetic field lines) produce small amounts of plasma locally heated to flare-like temperatures (5 - 10 MK). In addition to local heating, nanoflares drive chromospheric evaporation that contributes mass to the corona. Compelling evidence for this mechanism is widespread faint emission from plasma at flare-like temperatures such as that detected by the EUNIS sounding rocket in 2013. Further evidence includes faint blueshifted components in the wings of line emission indicative of chromospheric evaporation. With sufficient sensitivity, the occurrence of nanoflare heating can be investigated in active regions, quiet areas, and other solar features.

To summarize, spectroscopic capabilities needed to resolve key questions regarding flare energy release and coronal heating by nanoflares include: (1) high spectral resolution, to enable measurement of unblended profiles of numerous emission lines; (2) high sensitivity with a wide dynamic range, to enable detection of faint line emission as well as weak wing components; (3) comprehensive temperature coverage, observing lines formed at log T separated by 0.1 or 0.2 dex between at least 20,000 K and 20 MK; (4) an absolute wavelength scale, to enable Doppler velocity measurements accurate to within 1 km/s or better; (5) simultaneous measurements over spatial area comparable in size to active regions ($4' \times 4'$); (6) spatial resolution sufficient to resolve loop strands and the immediate vicinities of reconnection sites ($< 1''$); (7) cadence short enough to monitor evolution of the solar atmosphere during periods of most rapid change (< 1 s).