YOHKOH AND NON-THERMALITY IN FLARES

H. S. HUDSON
SPRC, ISAS, 3-1-1 Yoshinodai, Sagamihara-shi, Kanagawa 229, Japan

The *Yohkoh* observatory carries X-ray instrumentation capable of almost definitive flare observations within its resolution limits of a few arc seconds. The data confirm the energetic predominance of the impulsive phase in flare development, interpreting this phase as the epoch of non-thermality (the heating process). The clues include the behavior of sources at the feet of coronal loops, including hard X-rays, soft X-rays, and white light, and extend to the long-duration events and to the motions of ejecta often seen in these and other flares.

Introduction

Let us characterize a solar flare by its time development in soft X-rays. This emission comes from normal radiative processes in coronal plasmas at high temperatures: free-free, free-bound, and discrete line emissions from highly ionized atoms. In simple cases the soft X-radiation increases rapidly during flare onset, and then decays in an almost exponential manner. We represent this apparently thermal radiation by its distribution in emission measure, and find that the bulk of the flare "differential emission measure" falls in the range 10-30 MK, depending upon the properties of the flare. A flare may consist of multiple outbursts of this basic pattern. The ionization states of iron range up to the hydrogen-like FeXXVI and presumably to the fully ionized state, but not predominantly; the helium-like FeXXV lines remain extremely bright.

If we turn to radiation characteristic of non-thermal particles, for example non-thermal bremsstrahlung above some threshold such as 30 keV (roughly 10 kT for the highest thermal temperatures in a flare), or the gyrosynchrotron emission from still higher energies, we find the clear pattern identified by Neupert (1968; see also Dennis and Zarro, 1993) and now termed the "Neupert effect": the non-thermal emissions tend to occur at or near the time of the rapid growth of the hot thermal plasma. This suggests strongly that the energization of the thermal plasma involves radical distortions of the originally Maxwellian distribution functions, and thermal ionization equilibria, of the pre-flare plasma. This is not unreasonable theoretically, and most flare models would probably predict such a relationship. It is interesting to note that the essential fact of the Neupert effect could already be seen in observations of the Earth's ionosphere in the 1950's: the "SFD" effect, due to impulsive excitation of transition-region and chromospheric lines, has the proper temporal relationship to the "SPA" effect. An SPA results from the occurrence of coronal hot plasma emission (the "sporadic coronal condensation", although this name is misleading) and was used by Kawabata (1960) and Elwert (1961) to predict the strong FeXXV and FeXXVI line emission later observed via space-borne observations.

This paper aims to describe the *Yohkoh* contributions to our understanding of flare energetics in the historical context; please refer to early reviews of solar flares (*e.g.* Švestka, 1976), concentrating on their descriptions of high-temperature and non-thermal effects. *Yohkoh* now carries advanced instrumentation for soft and hard X-radiation, generally providing the most definitive information available for the 1991 solar maximum. The bottom-line conclusion is that there remain many open questions regarding flare development, and that the resolution limits of *Yohkoh* data provide the greatest present obstacle to our understanding.

Nomenclature and Coulomb Collision Theory

Terminology presents a problem here. Non-thermal effects, explicitly meaning *non-Maxwellian distribution functions*, do not need to be impulsive, explicitly meaning *rapidly variable.* Likewise impulsive time variations may occur in some flare plasma regimes almost certainly Maxwellian in nature. Thus the nomenclature may not exactly match the phenomenology.

The impulsive phase should in principle give us some insight into the key physics involved in the departure from a relaxed plasma, *i.e.* the heating process. Plasma heating must occur in a variety of physical circumstances in the solar atmosphere, ranging from the photosphere (white-light flares) to the outer corona (solar-wind acceleration), so the distinction between "impulsive" and "non-thermal" must be elastic. We use the term "impulsive" here independent of time scale, to signify the time of the most violent energy release in a flare. We detect this energy release in a wide variety of radiations and mass motions, and interpret it as the result of conversion of magnetic energy stored in the coronal magnetic-field structure. In the sense that the impulsive phase involves the *heating* of flare plasma, it normally would require the distribution function to become non-Maxwellian, implying *non-thermality.* Heating would in most circumstances correspond to the creation of particle velocity distribution functions departing from distributions, from particle acceleration, discrete flows, or selective heating of (say) the ion component of the plasma. In fact the impulsive phase of a solar flare invariably accelerates high-energy particles, both electrons and ions. The non-thermality during the heating epoch is so strong that, from present knowledge, either electrons (*e.g.* Lin and Hudson, 1976) or ions (Ramaty *et al.*, 1995) might actually dominate the energy release process.

Coulomb collisions constitute the basic mechanism for establishing a Maxwellian distribution of particle velocities in a plasma (*e.g.* Spitzer 1965). The time scales for temperature equilibriation in a hydrogen plasma with $T_e \neq T_p$ vary as

$$\tau_{ee} : \tau_{pp} : \tau_{ep} :: 1 : \sqrt{m_p/m_e} : m_p/m_e$$

where the subscripts e and p designate electrons and protons, and the proton/electron mass ratio $m_p/m_e = 1836$; τ_{ee} for example represents the relaxation within the electron distribution, and τ_{ep} gives the time scale for electon and proton temperatures to equalize. The time scales for ions heaver than hydrogen increase with Z^2, and with temperature as $\mathrm{T}^{3/2}$; for particles in the non-thermal tails of the distribution slightly different rules apply, but the time scales generally become longer. We can get a feeling for these relationships by noting that $\tau_{ee} \sim 0.23$ sec at a temperature of 3×10^7 K and a density of 10^8 cm^{-3}. Thus even the fastest Coulomb relaxation times do not differ by orders of magnitude from observed flare time scales, at representative temperatures and densities.

Coulomb collisions always occur, but there may be other mechanisms leading to relaxation via wave-particle interactions. From the basic Coulomb collision theory alone we must conclude that non-thermal particle distributions commonly occur during flare energy release, even in the electron population, and that electron and ion temperatures almost certainly differ.

Yohkoh and Impulsive-Phase Phenomena

Yohkoh carries both hard X-ray and soft X-ray telescopes, and the data illustrate the terminology problem as well as contribute substantially to our understanding of the physics. The HXT gives views of both thermal and non-thermal plasmas; in spite of the nominal lower-energy threshold of 13 keV, implying electron energies far in the tail (more than 5 kT) of any flare Maxwellian distribution. HXT observations (*e.g.* Sakao, 1994) confirm the strong association of impulsive-phase hard X-ray emission with the footpoints of coronal magnetic loops (Hoyng *et al.*, 1981). SXT also has made several key observations related to the impulsive phase. We summarize some of these below.

White-light flare emission

The presence of transient white-light brightenings in the photosphere historically provided the first evidence for the existence of solar flares. To perturb the photosphere clearly requires energy release more intense than that needed to alter the corona, where the strongest flare effects occur. *Yohkoh* SXT has now given us a first systematic look at white-light flare emission from a space-borne telescope. We found observable emission transients to occur commonly in major flares (Hudson *et al.* 1992); the detectability for flares weaker than M in the GOES classification may be no more than an observational limitation. The white-light emission onsets closely match the hard X-ray onsets, supporting theories (Hudson, 1972) of energy transport in the upper photosphere by non-thermal electrons.

Impulsive soft X-ray footpoint emission

Soft X-ray observations also show impulsive effects (McTiernan *et al.* 1993; Hudson *et al.*, 1994a). Impulsive soft X-ray sources occur at loop footpoints, often commencing close in time to the hard X-ray burst but often delayed at their maxima; the spectra are softer than the loop sources themselves. The presence of impulsive soft X-ray emission is consistent with the occurrence of an impulsive component in the EUV (Woodgate *et al.*, 1983) as foretold by the SFD ionospheric effect (Donnelly and Kane, 1978).

Gradual flares

The Neupert effect extends to gradual flares, as shown by Dennis and Zarro (1993). Hudson *et al.* (1994b) found this to be true also of "slow LDE's", in other words long-duration events that also have slow rise phases. The flare of Feb. 21, 1992 (Tsuneta *it al.*, 1992) provides a well-studied example. The slow-rise events, as expected from the derivative relationship of the Neupert effect, have lower hard X-ray fluxes that last appropriately longer. Because the Neupert effect requires lower fluxes for gradual events, we need hard X-ray instruments with large collecting areas (such as the BATSE experiment on Compton GRO).

Timing of ejecta

The *Yohkoh* soft X-ray imaging observation allow us to follow mass ejections at high temperatures. These take a variety of forms, often related to coronal mass ejections (Hudson and Webb, 1997). Invariably the ejective motion (even when only detectable as a "dimming" or depletion of the soft X-ray corona) coincides with the rise phase of soft X-ray emission. Hudson *et al.* (1996) and Ohyama and Shibata (1997) have discussed individual examples from disk flares, for which we can clearly trace the motion and relate it to the flare emission. The association of acceleration with the timing of the impulsive phase can also be seen in the filament motions studied by Kahler *et al.* (1988). Shibata *et al.* (1995) have noted faint X-ray ejecta associated with all members of a complete sample of limb flares.

Conclusions

The *Yohkoh* data have in several ways extended our knowledge of the phenomena of the impulsive phase of a flare, abundantly confirming the general scenario known as the "Neupert effect". This implies that the main process of flare energy release has broad consequences, consistent with non-thermal particle distributions and non-local energy deposition. The current observations allow a sharpening of our knowledge of the relationship between energy release and coronal flare effects. This reveals interesting complexities, as we would expect from the varying conditions in which flares occur – note the differing qualities of the Neupert-effect relationship in the flares studied by Fárnik *et al.* (1997).

From these observations we conclude that the flare energy release has a broad-band character, with signatures distributed across the spectrum from meter-waves to γ-rays, and across many physically distinct environments in the solar atmosphere. The data seem consistent with energy transport by accelerated particles, in particular electrons in the >20 keV energy range. Neither the Neupert effect itself (observationally), nor large-scale magnetic reconnection (theoretically) predict or require these particles, which remain a difficult but central problem of flare physics.

With all of this knowledge, what do we need to learn? Most of the evidence from the impulsive phase points to particle acceleration, which we observe fairly directly via bremsstrahlung and nuclear emission lines. However we still have little idea where the acceleration occurs; recent works have pointed to the reconnection point, the slow shocks, the fast shock, or none of the above! We need new observations optimally put together in the form of simultaneous measurements over all spectral bands to resolve this crucial question. The measurements should include:

- *Higher angular resolution.* The TRACE data show clearly that the corona contains abundant structure unresolved at the arc-second level. The illuminated flux tubes do not appear to fill the whole volume, but the field must do so because of the nearly force-free nature of the field in a coronal active region; accordingly these new high-resolution observations must cover a wavelength range broad enough to define all of the coronal temperature regimes.

- Imaging spectroscopy. The velocity fields in the corona can help us disentangle the unresolvable third dimension, and allow us to detect the large-scale flows predicted by some models. The EUV and X-ray emission-line spectra also give access to all of the temperature regimes of the corona, as requested above, including the material at transition-region and chromospheric temperatures sometimes interspersed with the hot material.
- *High-energy radiations.* These radiations help to locate the energy release and to define the field connectivity. The hard X-ray and γ-ray spectra give information about non-thermal electrons and ions, respectively. HESSI (to be launched July 4, 2000; see Dennis *et al.*, 1996) will take the next step beyond the *Yohkoh* HXT in this area.
- *Particles and fields.* Because of the ubiquity of ejecta, both from flares (Shibata *et al.*, 1995) and from non-flaring active regions (Uchida *et al.*, 1992), it is now even more essential than before to use the information contained in solar-wind particles, plasma, and fields to obtain a proper understanding of the coronal processes.

How can these new observations contribute to our knowledge – in what ways do the current observations fail to satisfy our curiousity about how flares work? I would like to note that flares occur in a kind of quadruple transition region. As we move outward, the radiation goes from optically thick to optically thin; the plasma temperature jumps from photospheric to coronal; the plasma of the solar atmosphere undergoes a transition from collisional to non-collisional predominance; and finally the plasma beta of the active regions makes a complicated transitions between high and low values. This makes for great complexity in the theoretical description of the phenomena, which may have to involve processes spanning all of these regimes. This consideration applies to numerical model simulations of these processes as well as to theoretical concepts. For example, a credible simulation of flare energy release cannot be done within ideal MHD, because this theory does not incorporate particle acceleration or the non-local energy transport by the accelerated particles.

With this complexity in mind, it appears that our understanding of the physics of solar flares is limited by the observations, rather than the competence of the models. It is in this sense that the primary need now is for a broadly-based systematic improvement of observational material in all of the areas mentioned above.

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REFERENCES

Dennis, B. R., and Zarro, D. M., Solar Phys. **146**, 177 (1993).
Donnelly, R. F., Kane, S. R., ApJ **222**, 1043 (1978).
Elwert, G., JGR 66, 391 (1961).
Dennis, B. R., Lin, R. P., Canfield, R. C., Crannell, C. J., Emslie, A. G., Holman, G. D., Hudson, H. S., Hurford, G. J., Ling, J. C., Madden, N. W., and Ramaty, R., *Proc. S.P.I.E.* 4-9 August (1996).
Fárnik, F., Hudson, H. S., and Watanabe, T., A&A **320**, 620 (1997); erratum **324**, 433 (1997).
Hoyng, P., Duijveman, A., Machado, M. E., Rust, D. M., Švestka, Z., Boelee, A., De Jager, C., Frost, K. T., Lafleur, H., Simnett, G. M., Van Beek, H. F., and Woodgate, B. E., ApJ (Lett.) **246**, L155 (1981).
Hudson, H. S., Solar Phys. **24**, 414 (1972).
Hudson, H. S., Acton, L. W., Hirayama, T., and Uchida, Y., PASJ **44**, L77 1992.
Hudson, H.S., Strong, K.T., Dennis, B.R., Zarro, D., Inda, M., Kosugi, T., and Sakao, T., ApJ. (Lett.) **422**, L25 (1994a).
Hudson, H. S., Acton, L. W., Sterling, A. S., Tsuneta, S., Fishman, J., Meegan, C., Paciesas, W., and

Wilson, R., in Y. Uchida, T. Watanabe, K. Shibata, and H. S. Hudson (eds.), *X–ray Solar Physics from Yohkoh* (Universal Academy Press, Tokyo), p. 143, (1994b).

Hudson, H. S., Acton, L. W., and Freeland, S. R., ApJ **470**, 629 (1996).

Hudson, H. S., and Webb, D. A., in N. Crooker, J. Joselyn, and J. Feynman (eds.), *Coronal Mass Ejections: Causes and Consequences*, Geophysical Monographs #99, p. 27 (1997).

Kahler, S. W., Moore, R. L., Kane, S. R., and Zirin, H., ApJ **328**, 824 (1988).

Kawabata, K. Rept. Ion. Space Res. Japan XIV, 405 (1960).

Lin, R. P., and Hudson, H. S., Solar Phys. **50**, 153 (1976).

Neupert, W. M., ApJ (Lett.) **153**, L59 (1968).

McTiernan, J.M., Kane, S.R., Loran J.M., Lemen J.R., Acton L.W., Hara, H., Tsuneta, S. and Kosugi, T., ApJ (Lett.) **416**, L91 (1983).

Ohyama, M. and Shibata, K., PASJ **49**, 249 (1997).

Ramaty, R., and Mandzhavidze, N., Kozlovsky, B., and Murphy, R. J., ApJ (Lett.) **455**, L193 (1995).

Sakao, T., Ph.D. thesis, Tokyo University (1994).

Shibata, K., S. Masuda, M. Shimojo, H. Hara, T. Yokoyama, S. Tsuneta, T. Kosugi, and Y. Ogawara, ApJ **451**, L83 (1995).

Spitzer, L., *The Physics of Fully-Ionized Gases*, New York: Interscience (1965).

Švestka, Z., *Solar Flares*, Kluwer (1976).

Tsuneta, S., Hara, H., Shimizu, T., Acton, L. W., Strong, K. T., Hudson, H. S., and Ogawara, Y., PASJ 44, L63 (1992).

Uchida, Y., McAllister, A., Strong, K. T., Ogawara, Y., Shimizu, T., Matsumoto, R., and Hudson, H. S., PASJ 44, L155 (1992).

Woodgate, B. E., Shine, R. A., Poland, A. I., Orwig, L. E., ApJ **265**, 530 (1983).