SOLAR GAMMA–RAY ASTRONOMY IN THE 1990'S AND THE GAMMA–RAY OBSERVATORY

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ABSTRACT

Solar high–energy astrophysics has flourished in the decade of the 1980's, and γ–radiation has played a major role in the advances of our understanding. This was due in large part to the wealth of line and continuum data from the γ–ray experiment on board the Solar Maximum Mission. The observations from this instrument showed that ion acceleration often occurs in solar flares, often impulsively (time scales on the order of seconds), and often to cosmic–ray energies (> 100 MeV/nucleon). The Gamma–Ray Observatory carries a new generation of large instruments with extraordinary sensitivity. We expect that GRO observations will make many new discoveries possible in "classical" solar high–energy astrophysics, *i.e.* solar flare studies, but it should be noted that the GRO sensitivity approaches the level needed for the detection of subtler solar γ–ray sources associated with the quiet Sun or weaker forms of magnetic activity. The Sun also has potential "nuisance value" for non–solar observations, especially in the initial years of GRO operation. This paper makes the following recommendations:

- The GRO experimenters should make special efforts in the early period of operation to understand the solar response of their instruments; and
- The "quiet" Sun is worth observational attention at all energies.

INTRODUCTION

Stars (*e.g.* the Sun) are unusual objects of interest for γ–ray astronomers. However the Sun is nearby, so that we can rather easily observe relatively faint γ–ray emissions. Fortunately, and perhaps surprisingly, the Sun displays a broad spectrum of high-energy radiations and fundamental physical processes, including the generation of "cosmic rays" and γ-rays[1] up through the π° decay region $\sim$100 MeV at least. These high-energy radiations are accompanied by non-thermal radio emissions of great complexity, so that the overall spectrum of the Sun during active conditions — not counting the optical and infrared emissions from its photosphere — crudely resembles that of an active galactic nucleus.

Solar γ-ray astronomy made major progress during the solar maximum of 1981, especially via the extensive observations made by the γ-ray spectrometer on board the Solar Maximum Mission (SMM). The Gamma Ray Observatory (GRO) will begin its life during the the present maximum, and we expect that its sophistication will make important new advances in our understanding of solar flares and related phenomena. This paper reviews the general background of solar γ-ray astronomy and makes some suggestions for scientific emphasis in GRO observations. GRO will contribute substantially to solar physics in the 1990's. Table 1 lists future space missions with substantial solar γ-ray capability (adapted from Kurfess, 1988); GRO is notable in this list for offering tremendous improvements in detection sensitivity, timing, and wavelength coverage.

Table 1
Future Missions with Solar γ-ray Capability

Mission	Launch Date	Observations
GRO	March 1990	γ-rays 0.005–300 MeV
GRANAT	late 1980's	Non-solar γ-rays
Solar-A	August 1991	X-ray imaging 0.1–100 keV
MAX'91	Balloons	γ-ray imaging <1 MeV
MAX'91	Balloons	Ge* spectroscopy (> 15 keV)
Wind	Early 1990's	Ge spectroscopy (> 25 keV)
Mars Observer	1992	Ge spectroscopy (> 40 keV)

*Germanium spectrometers can have resolution to the order of 1 keV, and can therefore observe the details of γ-ray emission line shapes, for example.

The Sun will necessarily also have an adverse impact on GRO non-solar observations, as sketched out in Section 4 below. Figure 1, showing solar hard X-ray data, should make the nature of the problem immediately clear to the GRO researchers. The HXRBS instrument on board the Solar Maximum Mission (SMM) detected as many as 60 solar hard X-events per day above a threshold of 25–33 keV (*e.g.* Dennis, 1985). This instrument has a sensitive area of only 71 cm^2, and relatively high

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[1] We loosely use the term "γ-ray" here to mean any radiation detected above about 100 keV, even if its origin is thought to be ordinary electron bremsstrahlung (as is the case even above 10 MeV for impulsive solar emission).

background counting rates; we therefore can assume that the much more sensitive GRO instruments[2] will to respond to all solar events in this class and probably to even more numerous smaller events.

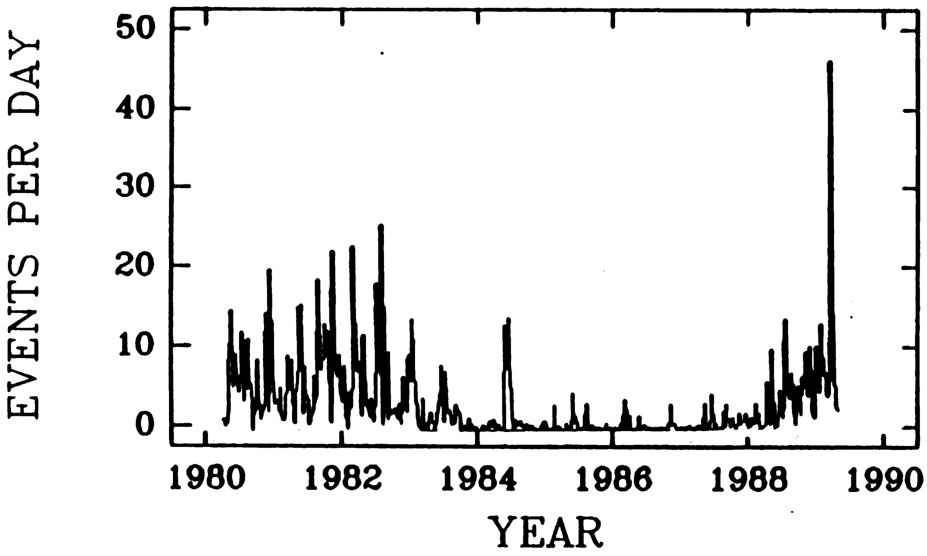

Figure 1. Occurrence rate by one-week averaging of hard X-ray bursts observed by the HXRBS instrument on board the Solar Maximum Mission (Dennis, 1989) above 20 keV photon energy, with an effective area of about 72 cm^2. The onset of Solar Cycle #22 can clearly be seen.

TOPICAL REVIEW OF SOLAR γ-RAY ASTROPHYSICS

General background

The past solar cycle has brought solar γ-ray astronomy into the mainstream of solar physics, in the sense that the SMM observations revealed, for the first time, the existence of a broad range of phenomena associated with many aspects of solar-flare phenomenology. Before SMM, only a few flares had been seen in γ-radiation (*e.g.* Chupp, 1984), and therefore the significance of γ-ray observations might have seemed somewhat marginal from the point of view of general solar physics. It should be noted that progress in solar flare research now generally requires multi-wavelength observations, because of the spatial inhomogeneities of the flare struc-

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[2] One of the eight large-area modules of the BATSE instrument alone, for example, has a geometrical area of some 2000 cm^2.

tures. The γ-rays fill an important niche in the range of observational capabilities needed for further progress.

Solar γ–radiation reflects the presence of energetic ions and relativistic electrons, accelerated by one or more distinct mechanisms. The identification of the physics of the acceleration process — the mechanism of acceleration, the plasma physics of its location, and the source of the energy for the particle acceleration — represents one of the major tasks of solar γ-ray astronomy.

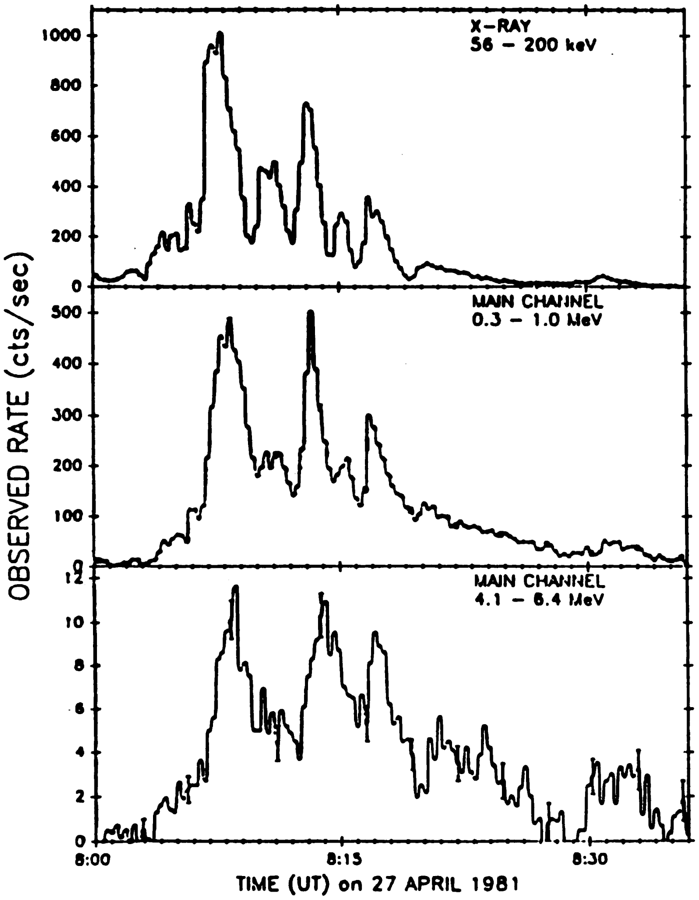

Figure 2. Relative timing of hard X–ray and γ–ray emissions from the major solar flare observed by SMM April 27, 1981 (*e.g.* Chupp, 1984).

Timing observations

The GRO instruments have large areas and hence good time resolution because of favorable photon statistics. The imaging capability of GRO, unfortunately, is only good enough barely to resolve the solar disk in the best case, and therefore has little importance for solar studies. On the other hand, the timing information, together with relatively coarse spectroscopic capability of the GRO scintillation counters, is intrinsically interesting because of the high sensitivity of the large GRO instruments and their broad spectral coverage. The time structure of solar γ-ray emission — both by itself and in comparison with other wavelengths — is a powerful astrophysical tool. Via time–series analysis, we can study the structure of the emitting sources, for example by comparison of time delays between radiations formed at different heights in the solar atmosphere. This tool is most useful when we have true imaging observations at other wavelengths, as we can do on the Sun; both high–energy (*e.g.* the X–ray imaging of Solar–A) and low–energy (*e.g.* routine Hα "patrol" images) should be available.

Figure 2 shows a well–known example of the time relationships between the components of high–energy emissions in a flare observed by SMM. This striking event — the subject of much analysis — exhibited several spikes of not–quite–simultaneous emission in the microwave, hard X–ray, and γ–ray spectral regions. Clearly our ability to interpret these subtle timing differences depends upon having precise data, which for γ–rays depends upon large–area detectors with large counting rates.

Spectroscopic observations

The field of astrophysical γ–ray spectroscopy can truly be said to have begun with the solar–flare observations of SMM, as illustrated in the spectrum shown in Figure 3. This exhibits many features of different types, including a broad underlying continuum attributed to electron bremsstrahlung, plus excesses in the nuclear emission–line domain of a few MeV. Most of the γ–ray line emission is due to nuclear deexcitations of ambient nuclei following interactions with the accelerated particles (by inference, in the photosphere and chromosphere); however the 2.22 MeV line of deuterium formation, the 0.511 MeV line of positron annihilation, and the so–called α–α lines also give some information about the projectile particles directly (*e.g.* Murphy, 1989).

The solar γ–ray spectroscopy results to date have largely been from inorganic scintillation counters (but see Prince *et al.*, 1982). The GRO will extend such observations with the advantages of large area, high counting rate, and therefore good counting statistics. For example, the BATSE spectroscopy detectors contain NaI(Tℓ) totalling some three times the volume of the γ–ray instrument on SMM, and the other GRO detectors are even larger.

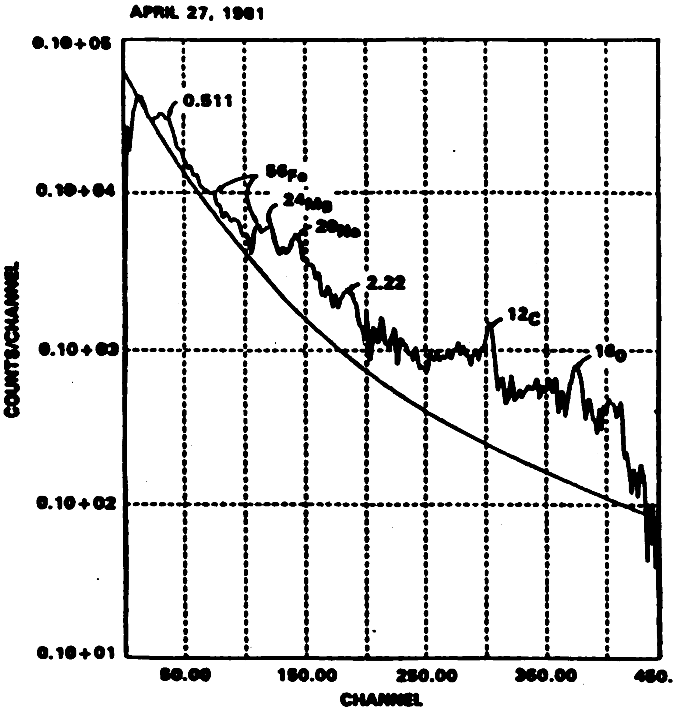

Figure 3. Spectrum of γ–rays from the flare of April 27, 1981, as observed by SMM (Chupp, 1988).

Occurrence patterns

In the absence of imaging data, indirect methods of inference about source structure become necessary (and are the rule, of course, for most non–solar observations). The comparison of time profiles at different photon energies, mentioned above, is one example. Another remarkable SMM observation appears in Figure 4, which shows the solar disk distribution of the locations of Hα flares responsible for >10 MeV continuum emission (Rieger *et al.*, 1983). From this occurrence pattern, it has been inferred that the emitting electrons have systematically downward motions, so that the inherent directionality of the relativistic bremsstrahlung creates the observed pattern of limb brightening.

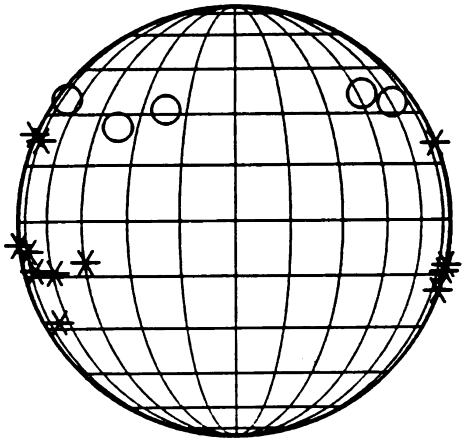

Figure 4. Distribution of Hα flares responsible for >10 MeV γ–ray continuum emission (via relativistic bremsstrahlung). The strikingly non–random pattern of these flares indicates downward streaming of high–energy electrons towards the solar photosphere (Rieger *et al.*, 1983). The points shown as circles are from 1989 (Dunphy, 1989). North is at the top, East at the left.

Limb occultation of a portion of a solar hard X–ray or γ–ray source can give information about its vertical structure (*e.g.* Hudson, 1978; see Kane, 1988, for "stereoscopic" observations involving multiple spacecraft). We may expect that the sensitivity of GRO will contribute greatly to the numbers of events for which solar limb occultation analysis can be carried out.

Neutron observations

The direct observation of solar neutrons by instruments on board SMM, in three events, was another observational coup (*e.g.* Chupp, 1984). Figure 5 shows a neutron source function inferred from these observations. The neutrons have at least two significant points of interest. First, they result from higher–energy primaries, on the average, and their observation thus complements that of the inelastic–scattering lines in determining the primary spectrum. Second, the outward–bound neutrons decay after straight-line flight away from the Sun, thus depositing protons and electrons in otherwise inaccessible regions of space (Evenson *et al.*, 1984).

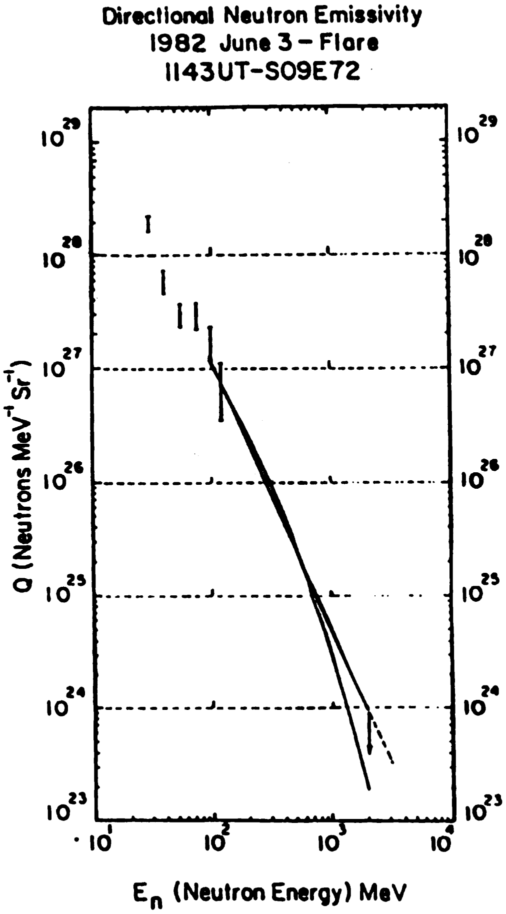

Figure 5. Source function of neutrons in the solar atmosphere inferred from SMM and direct observations, for the event of June 3, 1982 (Chupp, 1988).

The quiet sun

Solar γ–ray emission in the absence of solar flares represents an interesting possibility for highly–sensitive instruments such as those of GRO. One basic underlying source for such γ–rays would be the equilibrium spectrum of atmospheric secondary radiations produced by primary galactic cosmic rays.

The cosmic–ray secondaries include many channels ultimately generating energetic photons in a cascade, a phenomenon well–understood in the Earth's atmosphere, but never the subject of a detailed theoretical treatment for the Sun. To get a first–order approximation of the solar γ–ray luminosity, we could assume the solar surface brightness to be the same as that of the Earth, for which some measurements exist (see discussions in Chupp, 1976; and Hillier, 1984). This leads to the crude flux estimates in Table 2, which assume the terrestrial cosmic–ray "albedo" as a surface brightness for the Sun (Peterson *et al.*, 1966). Table 2 also includes an estimate of the Sun as a "negative source" because of its absorption of the diffuse γ–ray background flux. We note that the estimated flux levels are generally lower than the estimated continuum sensitivities of the GRO instruments. Kurfess *et al.* (1983) give a continuum sensitivity of $\sim 5 \times 10^{-5}$ for OSSE, but the differences probably do not exceed the uncertainties in the estimates.

Table 2
Solar Quiet γ–ray Flux

Photon Energy (MeV)	Continuum Flux $\gamma(\mathrm{cm}^2\ \mathrm{s})^{-1}$	Diffuse Background $\gamma(\mathrm{cm}^2\ \mathrm{s})^{-1}$
0.1 – 0.2	7×10^{-5}	-1.7×10^{-5}
1 – 2	8×10^{-6}	-1.0×10^{-6}
10 – 20	8×10^{-7}	-1.0×10^{-7}
100 – 200	8×10^{-8}	-1.0×10^{-9}

The terrestrial γ–ray flux is a function of latitude, because of the variation of cosmic–ray cutoff rigidity, and a strong function of angle relative to the limb. The strong limb brightening predicted and observed for the terrestrial γ–radiation (Thompson, 1974), results from the strongly downward momentum of the primary cosmic rays and their initial secondary products. The solar surface brightness would vary with position according to the large–scale distribution of magnetic field in the heliosphere, which modulates the cosmic–ray flux. Roughly, we would expect that the strong magnetic fields within solar active regions would result in a high rigidity threshold for galactic cosmic rays, and thus active regions would be considerably darker than coronal holes, where the weak magnetic field and open connectivity into interplanetary space would allow ready access of primary particles. This modulation also is well-known to have a solar-cycle dependence, in the sense that the sunspot maximum would correspond to a minimum of "intrinsic" solar γ-ray luminosity.

The spectrum of γ-radiation from the quiet Sun will have a stronger X-ray component than the terrestrial flux, because the low mean atomic number of the solar atmosphere will result in lower photoelectric absorption of the multiply Compton-scattered secondary photons. The γ-ray emission lines give information about elemental abundances, and since the cosmic-ray secondaries form in the deep photosphere, this information would be substantially different from that obtained from solar-flare γ-ray emission lines. However, the solar γ-ray lines should be quite weak relative to the continuum by comparison with the terrestrial data (*e.g.* Letaw *et al.*, 1989) because of the low solar abundances of heavy elements (O, N) which undergo spallation reactions with the primary cosmic rays in the Earth's atmosphere. Detailed theoretical calculations of the nuclear physics and radiative transfer should be carried out.

In addition to this base level of solar quiet-time γ-ray luminosity, there are other mechanisms at work connected with low levels of activity. The heating of the chromosphere and corona requires non-thermal dissipation of energy, which in the case of magnetic elements (active-region faculae and the chromospheric network) may well involve particle acceleration analogous to that seen in solar flares. If so, these structures would also provide a base level of quiet-time γ-ray luminosity. Similarly we can cite "microflares," flaring bright points, and filament-channel brightenings, all distinctly different phenomena observed in X-radiation, as possible sources of low-level γ-ray emission. Only highly sensitive observations, such as those possible with the large instruments on board GRO, could hope to discover these or other conceivable sources of "solar quiet" γ-ray luminosity.

Solar activity

The GRO instruments should each contribute substantially to the extension of solar-flare observations — the traditional domain of solar γ-ray astronomy — into new domains of sensitivity and spectral range. The details are not easily predictable, but the recent history of solar observations has shown that the following points are likely to be useful in considering how to employ GRO for solar-flare observations.

- The GRO data will be most useful in conjunction with other kinds of data, so that GRO support of observing campaigns, *e.g.* those involving the Very Large Array or other large radio telescope, would be especially desirable.

- The GRO data will contribute to the discovery of new and interesting physics in individual strong events, especially in the high-energy domain little studied thus far.

- The GRO data will be applicable at the lower end of the range of event sizes, where numerous smaller events can be well–studied in a statistical sense.
- A choice of observing modes early in the GRO mission, followed by systematic observations in these modes, will be helpful from the point of view of statistical analysis of a uniform data base.
- Automatic slewing the pointed instruments to the Sun upon specific trigger information may produce interesting late–phase observations, but the initiation of a flare should also be observed. Therefore, some "staring" observations should be scheduled during times of predicted high activity.

THE **DARK SIDE** OF THE SUN: SOLAR INTERFERENCE

The Sun provides many opportunities for γ–ray astrophysics, but also has to be regarded as a nuisance for many kinds of non–solar observations. The several types of interference include effects not only of solar γ–rays, which indeed should be relatively transient, but also of solar hard and soft X–rays, which can have extraordinarily intense fluxes and persist over long periods of time during conditions of solar activity:

- The occurrence of false triggers, which if not understood could re–set instrument observing modes in undesired fashions;
- The "wasted" telemetry resulting from solar triggers;
- The saturation of sensitive, large–area detectors, with sometimes unpredictable results;
- The production of additional dead time in large–area shield counters;
- The competition of solar radiation scattered off of spacecraft parts or the Earth's atmosphere and causing confusion.

To this list we could add several specific problems associated with the use of sensitive, large–area γ–ray instruments for solar observations as such. These include the "invisible counts" problem (*e.g.* Kane and Hudson, 1970), in which the lowest–level discrimination threshold of a given counter is set for pulse heights above the physical threshold for photons set by the shielding. This can result in a flood of small pulses which can substantially deteriorate counter performance. Pulse pile–up is also a major problem (*e.g.* Datlowe, 1978).

RECOMMENDATIONS

The first years of GRO observations will be most important: for solar physicists, this will be the peak of solar activity in Cycle 22, with many flares to observe. For the GRO experimenters in general, these first years will see a rapid improvement in their understanding of the complex operating modes of the sophisticated GRO instruments, each of which has a great deal of flexibility in terms of data handling, and of course in the pointing directions of the three directional instruments. The review and discussion in this paper lead to the following recommendations for GRO handling of the opportunities and problems presented by the Sun:

- During the initial year of GRO observation, the experimenters should make special efforts to understand the solar response(s) of each instrument; this knowledge will improve the quality of both the solar and non–solar observations.
- The GRO observers should be ambitious to observe the "quiet" Sun, in addition to the flare–related phenomena. The γ–ray spectrum of the quiet Sun, if bright enough to be observed, will contain a great deal of interesting physics and new discovery. The wide–field instruments on GRO may take advantage of this by scheduling pointed observations to include the Sun in their fields of view if possible.
- The GRO experimenters should note that solar γ–ray emissions are extremely interesting from the astrophysics point of view, in spite of the fact that most solar results will be > 3 sigma!

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