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太阳 γ 射线研究的新进展

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摘 要

概述了太阳 γ 射线研究的新进展，特别是最近 4 年的进展. 展望了未来的 HESSI 卫星空间探测研究.

关 键 词 太阳：耀斑 — 太阳： X 射线， γ 射线

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The Latest Progress in Solar Gamma-ray Studies

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Abstract

The latest progress in solar gamma-ray studies is summarized. More attention is paid to the progress made in last four years. Some expectations from future HESSI mission are also discussed.

Key words Sun: flares—Sun: X-rays, γ-rays

1 Introduction

The present solar gamma-ray studies are based on the data from GRS/SMM, CGRO, GRANAT, GAMMA-1, and WBS/Yohkoh. The work until 1995 were well summarized by Hudson & Ryan (1995), Ramaty & Mandzhavidze (1996), and Gan *et al.* (1994, 1998). In this review, more attention is paid to the progress in the last four years.

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2 Progress in Last Four Years

2.1 Gamma-ray line spectroscopy–abundance

There is a rapid progress in the gamma-ray spectroscopy especially on the abundance. Under different ratio of accelerated α/p, Murphy *et al.* (1997) and Share & Murphy (1997) theoretically calculated the ratio of α–α line to high-FIP line variation with power-law spectral index of injected energetic particles. By comparing with observations, they got that the ratio of accelerated α/p is about 0.5, rather than the photospheric value of 0.1. Mandzhavidze *et al.* (1997) pointed out that the results obtained by Murphy *et al.* (1997) and Share & Murphy (1997) depend on the assumed ambient abundance of He/O. If the abundance of ambient He/O is allowed to increase, the accelerated α/p can be still around 0.1. That is, there are two possibilities, either $\alpha/\mathrm{p} > 0.5$ with the photospheric He/O, or α /p $\sim$ 0.1 with a higher He/O. Share & Murphy (1998) distinguished these two possibilities via analyzing the 0.339 MeV line resulted from the interaction of injected α particles with ambient ^{56}Fe. The result shows that the ambient ^{4}He/H $\sim$ 0.1, supporting the α /p $\sim$ 0.5. Mandzhavidze *et al.* (1999) studied both the 0.339 MeV line and 0.847 MeV line, which are all from the interaction of injected α particles and/or protons with the target of ^{56}Fe. It is shown for 20 flares analyzed that the α/p is indeed bigger than 0.1. The studies show further that there is a temporal change in the composition of the flare plasma (Murphy *et al.* 1997) and of the accelerated heavier ions (Ramaty *et al.* 1997).

2.2 Directivity

The α–α line, resulting from accelerated α particles interacting with the target of ^{4}He, is a good indicator of angular distribution of injected α particles. But only until recently has the α–α line been resolved by using a special fitting technique developed by Murphy *et al.* (1990). Share & Murphy (1997) presented the α–α line profiles for the 19 GRS/SMM flares. In comparison with the theoretical profiles, it is found that an isotropic or a fan-beam angular distribution provides a good fit for most flares, while the downward beam angular distribution can be ruled out at least for two most intense flares. But Yoshimori *et al.* (1996) observed a redshift of the α–α line for the Yohkoh flare of 1991 November 15, implying a downward beam. Anyway, at present it seems to have more evidence to support the isotropic angular distribution.

2.3 Spectral evolution

It is well known that the energy spectrum of hard X-rays presents a soft-hard-soft variation with time for a majority of flares. Assuming a thick-target model, it is generally believed that the electron spectrum that leads to a power-law X-ray spectrum is also a power-law. Therefore, the spectral evolution of accelerated electrons has been well established. In comparison, we currently know very little on how the spectrum of interacting protons changes with time. This problem has recently been addressed by several authors. Gan (1998), by using the 2.223 MeV line time profile, proposed a new method to deduce the spectral evolution. He showed that the accelerated proton spectrum gradually hardens with time during a burst. This gradually hardening was also noticed by Gan & Rieger (1999), who used varied spectral indexes to fit the observed 0.511 MeV line time profiles. Another study on this topic was done by Murphy *at al.* (1997), where they compared the calculated line ratio of $^{20}Ne^{*1.63}/^{16}O^{6.13}$ with the observed ones. But they did not found obvious evidence on the spectral evolution, due to the poor time resolution. The behavior of spectral evolution will set a new constraint for the acceleration mechanisms.

2.4 Electron-dominated Events

The electron-dominated events have been studied in more detail. Vilmer *et al.* (1999) and Trottet *et al* (1998) studied two electron-dominated events. They showed that the so-called electron-dominated event is only a weak gamma-ray line flare, with the electron bremsstrahlung hardening above 500 keV. The energy carried by the protons above 1 MeV is still comparable to that of electrons above 20 keV. Moreover, Rieger *et al.* (1998) statistically studied the electron-dominated events and normal gamma- ray line flares. They quantitatively showed that electron-dominated events indeed constitute a new kind, since the gamma-ray line emissions in electron-dominated event is about one order of magnitude weaker than that of normal gamma-ray line flares. Contrary to electron-dominated event, Gan (2000) proposed a concept of proton-dominated event, in which the gamma-ray line emissions are extremely strong. Both electron-dominated and proton-dominated events require such an acceleration mechanism that sometimes it can effectively accelerate electrons, and sometimes it can work only for protons.

2.5 The off-limb flare of 1991 June 1

This flare is special that it occurs behind the limb $6^\circ \sim 9^\circ$, but it has a surprisingly intense neutron emission (Murphy et al. 1999), and that the ratio of $1.1 \sim 1.8$ MeV to $4.1 \sim 7.6$ MeV excesses ($\Phi_{1.1\sim1.8}/\Phi_{4.1\sim7.6}$) is exceptionally high (Ramay *et al.* 1997). A thin-target model is required to explain the high ratio of $\Phi_{1.1\sim1.8}/\Phi_{4.1\sim7.6}$ (Trottet *et al.* 1996; Ramaty *et al.* 1997), but thin-target model is not so effective in producing neutrons, except that the accelerated particle spectrum is harder than 2.0. This so hard spectrum of accelerated particles represents an extremely case never reported before.

2.6 Low/high energy cutoff

The power-law energy spectrum should have a low energy cutoff and high energy cutoff. The low energy cutoff, which sometimes manifestes the spectrum flattening, sets the total energy content carried by accelerated particles, while the high energy cutoff is related to the acceleration mechanism. Both parameters are very significant. Gan (1999) found an invariant point in the energy spectrum of non- thermal electrons for some GRS/SMM flares. This invariant point was explained as a reflection of low energy cutoff, which ranges from ten to several tens of keV. Petrosian et *al.* (1994) observed in one electron-dominated flare an intensity drop above 50 MeV. They attributed this intensity drop to a high energy cutoff of accelerated electrons. For the protons, the low energy cutoff deduced from the ratio of $\Phi_{1.63}/\Phi_{6.31}$ by Ramaty *et al.* (1995) is around 1 MeV. Alexander *et al.* (1994) analyzed Π^0-decay Doppler width for one flare and required a high energy cutoff at 500 ~ 800 MeV. Gan & Rieger (1999) studied the same flare as Alexander *et al.* (1994) did. They showed that in order to explain 0.511 MeV line by using a power-law spectrum, a high energy cutoff at about 500 MeV is required. We believe that the values of both low and high energy cutoffs should be case-dependent.

2.8 Large data set is now available

Vestrand *et al.* (1999) published the GRS/SMM atlas of gamma-ray flares. It covers totally 258 flares observed from February 1980 to November 1989. The data include: time profiles, time-integrated gamma-ray spectra, bremsstrahlung fluence, power-law spectral index, narrow nuclear line fluence, 0.511 MeV line fluence, 2.223 MeV line fluence, > 10 MeV fluence, and so on. Another atlas of the flares (100 keV~100 MeV) observed with Phebus/GRANAT was given by Terekhov *et al.* (1996), which covers totally 110 flares from 1991 to 1994. Both atlas provide a good data set for further statistical studies.

2.9 Acceleration mechanisms

The recent progress in acceleration mechanisms has been well reviewed by Miller *et al.* (1997). It seems that the stochastic acceleration is the most promising mechanism in the impulsive solar flares, especially that it can explain the abundance enhancement of accelerated heavier nucleus, that shock acceleration may play an important role in powering gradual flares, and that DC electric field acceleration can be used to explain the electron acceleration up to 200 keV. But for each mechanism, more detailed studies are quite necessary. Holman (1999) recently argued that the DC electric field can even accelerate electrons to 1 GeV and can also result in abundance deviation.

3 Expectation from HESSI

Above we have seen that although the studies on solar gamma-rays have been undergoing a great progress in recent years, there are still some insurmountable barriers, that is, the observed data are all from the medium or low energy resolution detectors. These make some studies and conclusions very ambiguous and vague. The HESSI mission, with high energy resolution detectors of germanium, will provide an excellent chance to update the knowledge of solar gamma-rays, which in particular include: gamma-ray spectroscopy, ambient plasma abundance, accelerated particle abundance, accelerated particle spectra, nuclear line profiles and particle angular distribution, 0.511 MeV line formation, 2.223 MeV line time profile, gamma-ray spectral imaging, and so on. It is anticipated that with the launch of HESSI in June, 2001, the solar gamma-ray studies will go into a new era.

References

1 Alexander, D., Dunphy, P. P., and MacKinnon, A. L. Solar Phys., 1994, 151: 147

2 Gan, W. Q. Progress in Astron., 1998, 16: 222

3 Gan, W. Q. Ap. J., 1998, 496: 992
4 Gan, W. Q. ApSS, 1999, 260: 515
5 Gan, W. Q. ApSS, 2000, 274: 481
6 Gan, W. Q., Lin, C. M. Progress in Astron., 1998, 16: 321
7 Gan, W. Q., Rieger, E. Solar Phys., 1999, 186: 311
8 Gan, W. Q., Zhang, H. Q. Progress in Astron., 1994, 12: 169
9 Holman, G.H. in R. Ramaty and N. Mandzhavidze (eds.), High energy solar Physics: Anticipating HESSI, 2000, ASP Conf. Series, 206: 414
10 Hudson, H. S., Ryan, J. Ann. Rev. Astron. Astrophys., 1995, 33: 239
11 Mandzhavidze, N., Ramaty, R., Kozlovsky, B. Ap. J., 1997, 489: L99
12 Mandzhavidze, N., Ramaty, R., Kozlovsky, B. Ap. J., 1999, 518, 918
13 Miller, J. A. J. Geophys. Res., 1997, 102: 14631
14 Murphy, R. J. *et al.* Ap. J., 1990, 358: 298
15 Murphy, R. J. *et al.* Ap. J., 1997, 490: 883
16 Murphy, R. J. *et al.* Ap. J., 1999, 510: 1011
17 Petrosian, V., MCTiernan, J. M., Marschhauser, H. Ap. J., 1994, 434: 747
18 Ramaty, R. Mandzhavidze, N. AIP Conf. Proc., 1996, 374: 533
19 Ramaty, R. *et al.* Ap. J., 1995, 455: L193
20 Ramaty, R. *et al.* Ap. J., 1997, 479: 458
21 Rieger, E., Gan, W. Q., Marschhauser, H. Solar Phys., 1998, 183: 123
22 Share, G. H., Murphy, R. J. Ap. J., 1997, 485: 409
23 Share, G. H., Murphy, R. J. Ap. J., 1998, 508: 876
24 Terekhov, O. V. *et al.* Astron, Letter, 1996, 22: 362
25 Trottet, G. *et al.* AIP Conf. Proc., 1996, 374: 153
26 Trottet, G. *et al.* Astron. Astrophys., 1998, 334: 1099
27 Vestrand, W. T. *et al.* Ap. J. Suppl. Ser., 1999, 120: 409
28 Vilmer, N. *et al.* Astron. Astrophys., 1999, 342: 575
29 Yoshimori, M. *et al.* in Y.Uchida, T. Kosugi, and H. S. Hudson (eds.), IAU Colloquium 153 Proc., 1996, 573