Extremely High Energy Cosmic Rays—Experiments, Theories and Future Direction—
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X-Ray Observations of Particle Accelerators in the Universe

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I present three topics on X-ray observations of particle accelerators in the universe. The first one is on observational evidences showing that particle accelerations really take place in supernova remnants. An observational trial to determine how largely the kinetic energy of matter is converted to that of non-thermal particles through a shock is also briefly reviewed. The second topic is on jet ejections from Galactic superluminal source, GRS1915+105. Some observational results from this source seem to indicate that jet ejections are associated with transitions between two states of an accretion disk, a standard-disk state and a slim-disk state. The third topic is on particle accelerations in clusters of galaxies. Although the observations are still too poor to have a definite answer, this issue is very important to determine how much the energy content of non-thermal particles is in our Universe.

KEYWORDS: particle accelerations, jet ejections, supernova remnants, Galactic superluminal sources, clusters of galaxies

§1. Particle accelerations in supernova remnants

1.1 SN1006

One of the most remarkable findings with ASCA is detection of a prominent non-thermal component from SN1006.[1] The ASCA observation of SN1006 showed that although the X-ray spectrum of the central part of the remnant revealed prominent emission lines of highly ionized heavy elements characterizing its thermal origin, the spectrum from the rim did not exhibit such a thermal nature. The rim spectrum can be reproduced by a power law with a photon index of 2.7 and is consistent with being in a range above a break of a synchrotron emission extrapolated from the radio spectrum (see Fig.1 of Naito et al. (2000)[2]). If the X-rays are really emitted through synchrotron emission, the electrons should be accelerated up to ~ 100 TeV ($\gamma \sim 10^8$). Presence of such high energy electrons were strongly supported by TeV gamma-ray detection from the rim of this supernova remnant by the CANGAROO experiment.[3] The TeV gamma-rays can be explained to be an inverse Compton emission of cosmic micro-wave background by high energy electrons with $\gamma \sim 10^{7-8}$. The wide-band spectrum of the rim of SN1006 (see again Fig.1 of Naito et al. (2000)[2]) shows that an electron distribution can reproduce both the radio and X-rays through the synchrotron emission and the TeV gamma-rays through the inverse Compton emission of MCB photons simultaneously under reasonable assumptions.

By investigating the synchrotron and the inverse Compton emissions, we can estimate the strength of the magnetic field and the Lorentz factor, γ at the break of the electron distribution, to be several gauss and $\sim 10^7$, respectively. Then, the total energy of the non-thermal electrons in the remnant, E_e, is roughly estimated by the following equation as

$$L \simeq \frac{4}{3}\frac{\sigma_T}{m_e c} < \gamma > \frac{B^2}{8\pi} E_e.$$

When the X-ray luminosity, $L \sim 10^{35}$ erg/s, the average Lorenz factor, $< \gamma > \sim 10^7$, and the magnetic field, $B \sim 3\mu$ gauss, E_e is estimated to be about 10^{48} erg. Here, σ_T, m_e, c are the cross section for Thomson scattering, the electron mass and the velocity of light. Since the electron energy is expected to be about a hundredth of the proton energy in cosmic rays, the total energy of the non-thermal particles in this SNR is roughly estimated to be 10^{50} erg. This amount of energy is consistent with an expectation from a hypothesis that the energy source of the Galactic component of cosmic rays is SNR's, and is about 10% of the typical energy given to a SNR.

1.2 E0102.2-7219

The unprecedented spatial resolution of the Chandra X-Ray Observatory enabled us to discuss how much the fraction of the shock energy going into cosmic rays directly from observations. Here, I introduce such a study by Hughes, Rakowski and Decourchelle (2000).[4)]

They compared an X-ray image of the young SNR in the SMC, E0102.2−7219 taken by Chandra, with those by Einstein and ROSAT and estimated the expansion rate of the SNR in the recent 20 years. From this expansion rate, the speed of the blast wave at the outermost edge of the X-ray emission is estimated to be ~6000 km s^{-1}. Once the blast wave velocity is determined, the post shock temperature is easily obtained as

$$kT_S = \frac{3}{16}\mu m_p v_S^2,$$

according to the strong shock conditions in the absence of cosmic-ray acceleration, where μ is a mean molecular weight. kT_S was estimated to be ~45 keV from the above blast wave velocity.

The electron temperature behind the shock is determined by an energy transfer rate from ions to electrons. The energy exchange through Coulomb interactions will provide the minimum electron temperature which is given as

$$\frac{dT_e}{dn_e t} = 0.13\frac{T_p - T_e}{T_e^{3/2}},$$

in cgs unit.

Hughes, Rakowski and Decourchelle (2000) calcurated this theoretically expected minimum temperature and compared with the electron temperature obtained from a spectral fit to an observed spectrum. They picked up the eastern rim of E0102.2-7219 in the Chandra image. Since the surface brightness sharply drops by more than two orders of magnitude beyond the edge of the rim, they identified that jump as the blast wave shock. Then, they fit the non-equilibrium ionized model (NEI) to the spectrum of the eastern rim region. From the spectral fit, the observed electron temperature is found to be 1 keV at highest, while the theoretically expected electron temperature should be no less than 2.5 keV. This discrepancy between the measurement and the theoretical consideration could be reconciled only when a significant fraction of the shock energy goes into generating non-thermal particles.

We obviously need further observations to

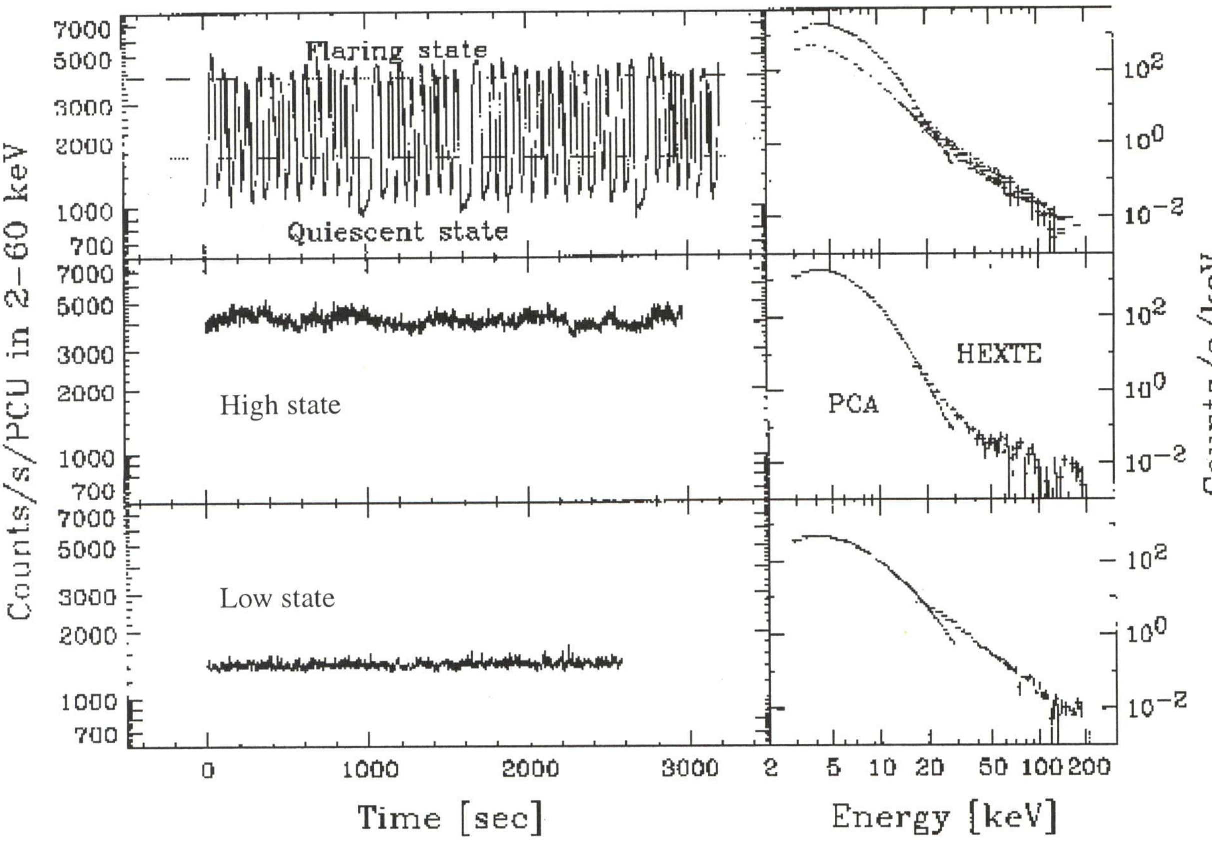

Fig. 1. Various states of GRS1915 + 105 observed with RXTE. Variable state (top panels): The source exhibited repetitive transitions between a high flux state and a low flux state. The flux and spectrum of each of the two states are almost the same as in the high and low state as shown below. High state (middle panels): The flux stays at a high level. The disk blackbody component is relatively strong in the spectrum. Low state (bottom panels): The flux stay at a low level. The power low component is dominant in the spectrum. Their flux variations (left) and spectra (right) are shown.

confirm this important indication. In particular, such a fine X-ray spectroscopy as to resolve the Doppler width of emission lines is expected to determine ion temperatures themselves in future.

§2. Jet ejection from the Galactic superluminal source GRS1915+105

GRS1915+105 is known to be the first source showing superluminal jets in our Galaxy.[5] This sources is also characterized by showing various temporal and spectral states. Fig.1 shows such examples. The spectra in various states are commonly approximated by a model composing of a soft component represented by the so-called multi-color disk-blackbody (DBB) spectrum[6] and a hard component. The spectrum of the hard component can be determined by analyzing the spectral change on a sub-second time scale on an assumption that the DBB component does not change on such a rapid time scale. Yamaoka

(2001)[7] performed such an analysis and found that the hard, rapidly valuable component can be approximated by a broken power-law model. Then, the spectra in the various states observed with RXTE in Jan., 1999 – Apr., 2000 were fitted with a model composing a DBB spectrum and a broken power law spectrum and the distribution of the best fit $R_{\rm in}$ and $T_{\rm in}$ values are shown in Fig.2. It is clearly seen from this figure that the data points are separated in two distinct groups, the high and the low temperature branch. This suggests presence of two states in the optically thick disk and they should probably be the standard disk[8] and the optically thick ADAF (advection dominated accretion flow) which is sometimes called as the slim disk.[9] If we plot relations between $R_{\rm in}$ and $L_{\rm DBB}$ obtained from the spectral fits, together with a line where $L_{\rm DBB} = L_{\rm Edd}$ and $R_{\rm in} = 3R_{\rm S}$ are simultaneously satisfied for any values of $M_{\rm BH}$, in Fig.3, In this figure, the high temperature branch is located in a region where $L_{\rm DBB} > L_{\rm Edd}$ and/or $R_{\rm in} < 3R_{\rm S}$. This situation in which $L_{\rm DBB} > L_{\rm Edd}$ and/or $R_{\rm in} < 3R_{\rm S}$ is consistent with a theoretical expectation from the slim disk.[10] Hence, the high temperature branch probably corresponds to a case of the slim disk, while the low temperature branch corresponds to a case of the standard disk.

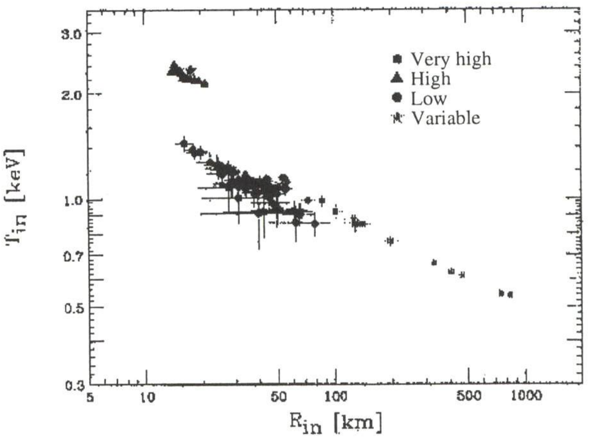

Fig. 2. Relation between the highest color temperature, $T_{\rm in}$, and the innermost radius, $R_{\rm in}$, of optically thick disks, obtained from spectral fits of a two-component-model to the spectra of GRS1915+105 observed with RXTE in various occasions.[7]

It is very interesting to note that the high–low transitions are often seen from this source as seen in the upper panel in Fig.1 and that mass ejections seem to take place in association with these transitions.[11] A jet ejection could occur when a standard disk changes to a slim disk or vice versa. More detailed observations of this

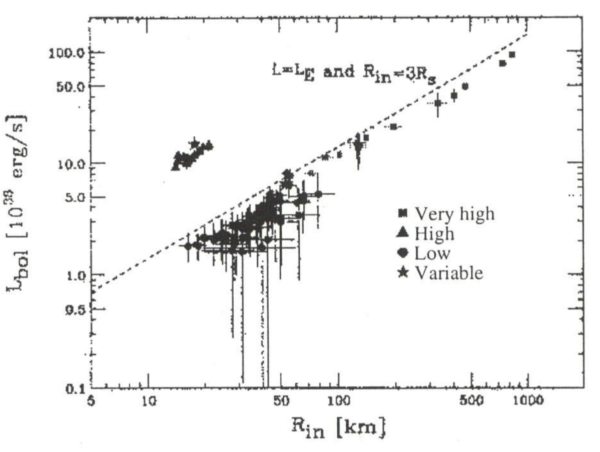

Fig. 3. Relation between the bolometric luminosity, $L_{\rm DBB}$, and the innermost radius, $R_{\rm in}$, of optically thick disks, obtained from spectral fits of a two-component-model to the spectra of GRS1915+105 observed with RXTE in various occasions.[7] A line where $L_{\rm DBB} = L_{\rm Edd}$ and $R_{\rm in} = 3R_{\rm S}$ are simultaneously satisfied for any values of $M_{\rm BH}$ is indicated.

source in future is anticipated.

§3. Particle accelerations in clusters of galaxies

Recently, observational evidences for presence of non-thermal emission from clusters of galaxies have begun to appear. In particular, its detection from the Coma cluster was reported in various wave bands, radio[12) ; EUV[13,14) ; X-ray.[15)

One possible mechanism for the non-thermal hard X-ray emission is inverse Compton emission of the cosmic micro-wave background.[15,16) In this case, the strength of magnetic field can be estimated by comparing the luminosity of the Synchrotron emission obtained from the radio observation with that of the inverse Compton emission obtained from the X-ray emission. Fusco-Femiano et al. (1999)[15) did it and pointed out that the estimated magnetic field ~0.16 μ gauss is significantly smaller than another value~0.4 μ gauss obtained from energy equipartition in the diffuse halo in the Coma cluster.

Another possible mechanism for the hard X-ray emission is non-thermal Bremsstrahlung by supra-thermal electrons with energies of 10 ~ 100 keV.[17,18) It is argued that low energy end of a population of electrons being accelerated to high energies by shock or turbulence could be responsible for the hard X-ray emission.

Although the non-thermal Bremsstrahlung is a plausible mechanism of the hard X-ray emission, we might need a fairly large amount of energy of non-thermal particles in the Coma cluster. According to Sarazin and Kempner (2000),[17) the number of the non-thermal electrons should be a few % of that of the thermal electrons. This means that the total energy of the non-thermal electrons would be ~ 10% of that of the thermal electrons. If the energy content of protons in the cluster is 100 times as large as that of electrons, the total energy of non-thermal particles could be ten times as large as that of the hot gas in the cluster of galaxies.

The present observations of non-thermal emissions from clusters of galaxies are still too poor to have a definite conclusion on the energy content of non-thermal particles in a cluster of galaxies. Future precise observations of the non-thermal emissions should obviously be necessary in order to know how large the energy content of non-thermal particles is in our universe.

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