Physics of Supernova Remnants in the XMM-Newton, Chandra and INTEGRAL Era: Final Report

February 13, 2005

Abstract

The research project was focused on the observation, modelling and interpretation of high energy photon emission from supernova remnants (SNRs). We bring together an international team of observers and theorists working with the XMM-Newton (ESA), Chandra (NASA), and INTEGRAL (ESA) spacecraft, as well as previous X-ray and gamma-ray space telescopes. The successful operation of these modern superb observatories, combined with ground-based radio and GeV-TeV gamma-ray observations, has made it possible to dramatically extend our knowledge of SNRs and their interaction with the interstellar medium (ISM). The major topics of the research project were:

- High resolution X- and γ-ray observations of SNRs to constrain the nucleosynthetic yields, the structure of the SN ejecta, conditions in the remnant and ISM, supernova explosion energy and efficient cosmic-ray production.
- Study of the physical processes of energy release in compact sources — pulsar wind nebulae.

1 Scientific rationale

Supernova remnants are unique laboratories for (astro)physicists as they contain states of matter and electromagnetic fields far beyond anything attainable on Earth. Detailed observational studies of SNRs have provided, and will continue to provide, unmatched ways to test our knowledge of fundamental physical laws in extreme conditions. Supernova (SN) explosions are the birthplaces of all of the elements heavier than iron. During the evolution of a SNR, these heavy elements and the light elements produced by stellar nucleosynthesis are ejected into the interstellar medium, affecting it much more intensely than the pre-SN stellar wind - the only way for the elements to get out from the stellar interior before the supernova explodes. Thus, the chemical evolution of galaxies, and clusters of galaxies as a whole, is driven by SNRs. Secondly, SNRs are the main sources of energy and momentum for the ISM. As the shock wave from the explosion moves outward from the exploded star, it sweeps a large volume of the ISM, heating it enough to change its properties on large scales and produce a host of observable consequences in several energy bands. Furthermore, a great deal of additional information comes to us because of the ability of SNRs to produce relativistic particles - cosmic rays - as well as hard photon emission. The shock waves and magnetic turbulence produced by these explosions are likely to be efficient accelerators of electrons and ions via the first- and second-order Fermi mechanisms, and it has long been believed that most galactic CRs are born in SNRs. When the shock-accelerated particles interact with the cold, dense ISM (and with the ambient radiation field), they generate hard photons via synchrotron, bremsstrahlung, inverse Compton, and pion-decay emission. The observation and interpretation of these high-energy photons provides a window on the violent processes taking place.

The high-energy study of SNRs has made enormous progress since 1999 with the launch of sensitive, arc-second resolution X-ray observatories - Chandra (NASA) and XMM-Newton (ESA). The high spatial resolution of Chandra offers unique possibilities to do spectroscopy, with moderate spectral resolution, of SNRs by spatially separating emission from different physical origins. Structures like bright knots, synchrotron rims, shocked ejecta, and swept-up ISM can be distinguished from neighboring structures and studied separately. Also, Chandra has been successful in detecting neutron stars in SNRs. A few very compact remnants in the Magellanic clouds could be studied using the High Energy Grating Spectrometer on Chandra, yielding exciting images in individual spectral lines. High-resolution X-ray spectroscopy using the Reflection Grating Spectrometer (RGS) on XMM-Newton is an equally powerful tool. With the RGS, high-resolution spectra are obtained from moderately extended (arcmin scale) SNRs, as well as from the narrow shock fronts of more extended (degree size) shell-like remnants. This allows accurate abundance determinations of important elements such as neon and oxygen, and detailed plasma diagnostics using, for example, the helium-like triplets of oxygen. In addition, the high sensitivity of the EPIC MOS and PN cameras of XMM-Newton allow imaging of nonthermal tails up to and beyond energies of 10 keV, as well as sensitive spectral imaging of the K-complexes of Si, S, Ca, Ar, and Fe.

The recently launched γ-ray observatory INTEGRAL opens a new era in fine γ-ray spectroscopy and imaging with its two main instruments: SPI and IBIS. These are supported by concurrent source monitoring with the secondary JEM-X and OMC instruments in X-rays and the optical band, making it possible to perform simultaneous observations of astrophysical phenomena over seven orders of magnitude in energy. Two technical key-points of the new mission are coded-mask imaging and the dithering strategy of observations which improve sensitivity and spectral resolution by suppressing systematic errors from spatial and temporal background variations. The spectrometer SPI performs spectral analysis of γ-ray point sources and extended regions in the 20 keV - 8 MeV energy range, with special concern for the 44Ti line and the positron annihilation line. The former is thought to be efficiently generated in supernova explosions, while the latter is likely to be produced in the vicinity of rotating highly-magnetized neutron stars that hide inside many SNRs. The imager IBIS performs wide-field imaging in the 15 keV - 10 MeV energy range with an angular resolution of 12' FWHM. It is a perfect partner to SPI for constructing detailed high-energy source images. Another task for IBIS is to identify γ-ray counterparts to the X-ray images of extended emission regions (e.g. SNRs) obtained by BeppoSAX, XMM-Newton, and Chandra. This facilitates the study of the fundamental mechanisms that accelerate particles and generate photons in SNR-ISM interaction regions and allows tests of the corresponding theories. The X-ray monitor JEM-X performs precise positioning (3' FWHM) of the sources studied by the main instruments in the 5-35 keV energy range and helps with source identification in crowded fields (like the Galactic Centre region). The study of SNRs is a major mission for INTEGRAL, and the current program of observations include long (megasecond range exposure) observations of Cas A, SN1006, γ-Cygni, IC443, and some other SNRs, both in guaranteed and in open time. Within the frame of our team project we obtained with *INTEGRAL* hard X-ray images (above 25 keV) of γ-Cygni SNR, which is the first case of hard X-ray imaging of galactic SNR.

2 Strategy

We assembled an experienced international team for this ISSI project that included people with direct access to data, as well as theorists capable of modeling and interpreting the complex results.

This combination leads directly to a multi-disciplinary approach wherein theory acts to connect the different wavebands and observations from the various spacecraft and ground-based telescopes.

We combined selected review talks intended to acquaint everyone with the major observational and theoretical aspects of SNRs and related issues with lively joint discussions on the frontier current research. We composed three working groups to discuss new observational programs and theoretical approaches on: (i) The physical conditions and composition of matter in SNRs and the structure of SN ejecta; (ii) Gas heating and cosmic-ray acceleration in the SNR collisionless shocks, with particular emphasis on particle injection problems; and (iii) The physics of pulsar wind nebulae.

3 The International Team

The following researchers from Germany, France, Italy, the Netherlands, Russia, Switzerland, UK, USA, Japan composed the *international team*:

F.Aharonian,J.Arons, J.A.M.Bleeker, H.Bloemen, F.Bocchino, A.M.Bykov, R.A.Chevalier, Th.Courvoisier, A.Decourchelle, R.Diehl, D.C.Ellison, J.Hughes, T.W.Jones, J.S.Kaastra, K.Koyama, F.Lebrun, A.Marcowith, G.Meynet, E.Parizot, J.Raymond, S.Reynolds, P.Slane, E. van der Swaluw, F.K.Thielemann, H.Tsunemi, J.Vink, R.Willingale.

The team coordinators were A.M.Bykov (Ioffe Institute, St.Petersburg, Russia), D.C.Ellison (North Caroline State University, USA), J.S. Kaastra (Space Research Organization of the Netherlands, Utrecht), F.Lebrun (CEA SAp, Saclay, France). The team leader — A.M.Bykov.

4 Scientific results

Following are some results of the work on SNRs being done within the *ISSI international team* SNR project.

- **The first hard X-ray image of a galactic SNR**

Spatially resolved images of the galactic supernova remnant G78.2+2.1 (γ-Cygni) in hard X-ray energy bands from 25 keV to 120 keV were obtained with the *IBIS-ISGRI* imager aboard the International Gamma-Ray Astrophysics Laboratory *INTEGRAL*. The images are dominated by localized clumps of about ten arcmin in size. The flux of the most prominent North-Western (NW) clump is $(1.7\pm0.4)\times10^{-11}$ erg cm^{-2} s^{-1} in the 25-40

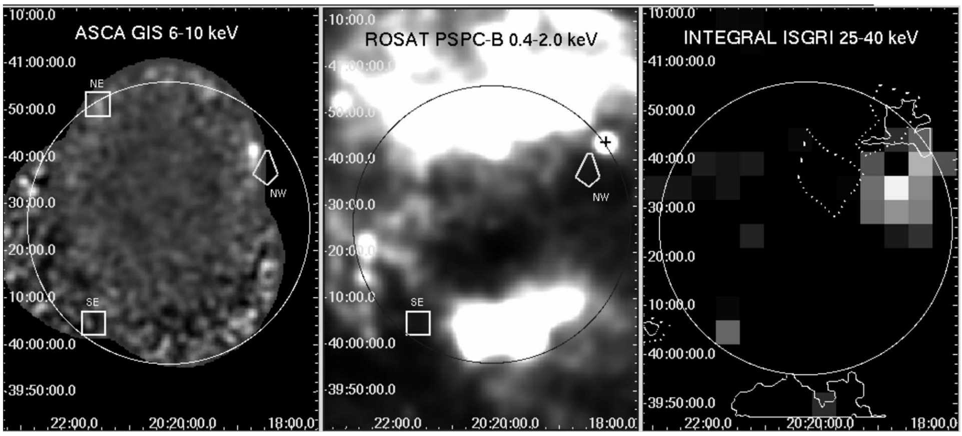

Figure 1: *Left*: *ASCA GIS* 6-10 keV grayscale map with an *INTEGRAL ISGRI* 25-40 keV 4.2 σ contour in the NW area. *Centre*: *ROSAT PSPC-B* 0.4-2.0 keV grayscale map with the same *INTEGRAL ISGRI* 25-40 keV 4.2 σ contour. *Right*: *INTEGRAL ISGRI* 25-40 keV significance map (linear scale) with H_α+[NII] 6560 Å 3×10^{-15} erg cm^{-2} s^{-1} arcsec^{-1} contours (dotted line) and [OIII] 5010 Å 3×10^{-16} erg cm^{-2} s^{-1} arcsec^{-1} contours (solid line) [optical data are from Mavromatakis (2003)]. The hard emission regions NW, NE, and SE are marked in the first two panels. The NE clump is seen with *ISGRI* only in the 40-80 keV band. The *RXTE PCA* field of view is indicated by the large solid circle. The black cross on the *ROSAT* map marks the position of the O9V star HD 193322 (20:18:07,+40:43:55). All maps are made for J2000.

keV band [see Fig.1]. The observed X-ray fluxes are in agreement with extrapolations of soft X-ray imaging observations of γ-Cygni by *ASCA GIS* and spatially unresolved *RXTE PCA* data. The positions of the hard X-ray clumps correlate with bright patches of optical line emission, possibly indicating the presence of radiative shock waves in a shocked cloud. The observed spatial structure and spectra are consistent with model predictions of hard X-ray emission from nonthermal electrons accelerated by a radiative shock in a supernova interacting with an interstellar cloud, but the powerful stellar wind of the O9V star HD 193322 is a plausible candidate for the NW source as well.

A.M.Bykov, A.M.Krassilchtchikov, Yu.A.Uvarov, H.Bloemen, R.A.Chevalier, M.Yu.Gustov, W.Hermsen, F.Lebrun, T.A.Lozinskaya, G.Rauw, T.V.Smirnova, S.J.Sturner, J.-P. Swings, R.Terrier, I.N.Toptygin

Astronomy and Astrophysics v. 427, L21-L24, 2004
http://www.arxiv.org/abs/astro-ph/0410688

- **New Constraints on the Structure and Evolution of the Pulsar Wind Nebula 3C 58**

  Patrick Slane, David J. Helfand , Eric van der Swaluw, Stephen S.Murray presented an investigation of the spectral and spatial structure of the X-ray emission from 3C 58 based on a 350 ks observation with the Chandra X-ray Observatory. This deep image, obtained as part of the Chandra Large Project program, reveals new information on nearly all spatial scales in the pulsar wind nebula (PWN). On the smallest scales we derive an improved limit of $T < 1.02\times 10^6$ K for blackbody emission from the entire surface of the central neutron star (NS), confirming the need for rapid, nonstandard cooling in the stellar interior. Furthermore, we show that the data are consistent with emission from a light element atmosphere with a similar temperature. Surrounding the NS, a toroidal structure with a jet is resolved, consistent with earlier measurements and indicative of an east-west orientation for the projected rotation axis of the pulsar. A complex of loop-like X-ray filaments fills the nebula interior, and corresponds well with structures seen in the radio band. Several of the structures coincide with optical filaments as well. The emission from the interior of the PWN, including the pulsar, jet, and filaments, is primarily nonthermal in nature. The power law index steepens with radius, but appears to also show small azimuthal variations. The outermost regions of the nebula require a thermal emission component, confirming the presence of an ejecta-rich swept up shell.

  P.Slane, D.J. Helfand , E. van der Swaluw, S.S. Murray

  Astrophysical Journal, v. 616, 403-413, 2004.

  http://www.arxiv.org/abs/astro-ph/0405380

- **Gamma-ray Observations of Explosive Nucleosynthesis Products**

  The various gamma-ray emission lines that are expected and have been observed from radioactive explosive nucleosynthesis products were discussed by J.Vink. The most important gamma-ray lines result from the decay chains of Ni-56, Ni-57, and Ti-44. Ni-56 is the prime explosive nucleosynthesis product of Type Ia supernovae, but Ni-56 is also a product of core-collapse supernovae. γ-ray line emission from its daughter product, Co-56, has been detected from SN1987A. The early occurrence of this emission indicates that some fraction of Ni-56, which is synthesized in the innermost supernova layers, must have mixed with the outermost ejecta. Special attention is given to the gamma-ray line emission of the decay chain of Ti-44, giving line emission at 68 keV, 78 keV, and 1157keV. Given its decay time of 86 yr, one expects this line emission from young supernova remnants. The Ti-44 production is very sensitive to the explosion properties. This makes Ti-44 an ideal tool to study the inner layers of the supernova explosion. The gamma-ray line emission from Ti-44 has so far only been detected from the supernova remnant Cas A. The detections, which were made by COMPTEL and BeppoSAX, suggest a Ti-44 yield of $(1.5 \pm 1.0)x10^{-4}$ solar mass. Vink presented some preliminary results of Cas A observations by INTEGRAL, which has yielded a 3 σ detection of the 68 keV line with the ISGRI instrument at a level consistent with the BeppoSAX results. A preliminary analysis of the vailable INTEGRAL-SPI data indicates that narrow line emission ($\delta v < 1000$ km/s) can be almost excluded at the 2σ level.

Jacco Vink

Accepted for publication in Advances in Space Research (2005).

http://www.arxiv.org/abs/astro-ph/0501645

- **Nonlinear Particle Acceleration at Reverse Shocks in Supernova Remnants** Without amplification, magnetic fields in expanding ejecta of young supernova remnants will be orders of magnitude below those required to shock accelerate thermal electrons, or ions, to relativistic energies or to produce radio synchrotron emission at the reverse shock. The reported observations of such emission give support to the idea that diffusive shock acceleration (DSA) can amplify magnetic fields by large factors. Furthermore, the uncertain character of the amplification process leaves open the possibility that ejecta fields, while large enough to support radio emission and DSA, may be much lower than typical interstellar medium values. D.C. Ellison, Anne Decourchelle and J. Ballet show that DSA in such low reverse shock fields is extremely nonlinear and efficient in the production of cosmic-ray (CR) ions, although CRs greatly in excess of mc^2 are not produced. These nonlinear effects, which occur at the forward shock as well, are manifested most importantly in shock compression ratios much greater than four and cause the interaction region between the forward and reverse shocks to become narrower, denser, and cooler than would be the case if efficient cosmic-ray production did not occur. The changes in the SNR structure and evolution should be clearly observable, if present, and they convey important information on the nature of DSA and magnetic field amplification with broad astrophysical implications.

D.C. Ellison, Anne Decourchelle, J. Ballet

Astronomy and Astrophysics v.429, 569-580, 2005.

http://www.arxiv.org/abs/astro-ph/0409182

- **Young core collapse supernova remnants and their supernovae** Massive star supernovae can be divided into four categories depending on the amount of mass loss from the progenitor star and the star's radius: red supergiant stars with most of the H envelope intact (SN IIP), stars with some H but most lost (IIL, IIb), stars with all H lost (Ib, Ic), and blue supergiant stars with a massive H envelope (SN 1987A-like). Various aspects of the immediate aftermath of the supernova are expected to develop in different ways depending on the supernova category: mixing in the supernova, fallback on the central compact object, expansion of any pulsar wind nebula, interaction with circumstellar matter, and photoionization by shock breakout radiation. The observed properties of young supernova remnants allow many of them to be placed in one of the supernova categories; all the categories are represented except for the SN 1987A-like type. Of the remnants with central pulsars, the pulsar properties do not appear to be related to the supernova category. There is no evidence that the supernova categories form a mass sequence, as would be expected in a single star scenario for the evolution. Models for young pulsar wind nebulae expanding into supernova ejecta indicate initial pulsar periods of 10-100 ms and approximate equipartition between particle and magnetic energies. Ages are obtained for pulsar nebulae, including an age of 2400 ± 500 yr for 3C58, which is not consistent with an origin in SN 1181. There is no evidence that mass fallback plays a role in neutron star properties.

  R.A. Chevalier,

  Astrophysical Journal, v. 619, 839-855, 2005.

  http://www.arxiv.org/abs/astro-ph/0409013

The ISSI is an ideal place to gather the international team and to conduct this multidisciplinary SNR research in the wide context of galactic chemical evolution, cosmic-ray origin, and fundamental problems of collisionless shock physics. We thank the ISSI staff for their support of this meeting. This support has been invaluable for us.

5 Appendix: Programm

5.1 "Physics of Supernova Remnants in the XMM-Newton, Chandra and INTEGRAL Era" (ISSI, Bern Dec.8-12, 2003)

- Monday, Dec.8, 2003.
- 11.30-12.00
- Welcome: ISSI, and the coordinators.
- Gamma-Ray Studies of SNRs:
- 13.30-14.00 F.Lebrun (Saclay) Current Status of INTEGRAL and SNR observations.
- 14.10-14.40 R.Diehl (MPE, Garching) SNR Diagnostics in the MeV Regime
- 14.50-15.30 F.Aharonian (MPfK, Heidelberg) Hard X-rays and TeV gamma rays from shell type supernova remnants
- 16.00-16.30 G. Kanbach (MPE, Garching) Gamma-Ray observations of SNRs and their compact cores.
- 16.40-18.00 Joint Discussion: Gamma-ray Observations of SNRs current status and perspectives.
  Tuesday, Dec.9
- X-ray Observations and Modeling of SNRs.
- 9.00-9.30 J.Kaastra (SRON, Utrecht) X-ray spectroscopy of SNR (XMM-Newton and Chandra)
- 9.40-10.10 K.Koyama (Kyoto University) Non Thermal X-ray filaments from SNRs
- 10.40-11.10 A.Decourchelle (Saclay) Observations of nonthermal X-rays in supernova remnants
- 11.20-11.50 F.Bocchino (Palermo Observatory) XMM-Newton Studies of SNR-Cloud Interactions
- 13.30-14.00 P.Slane (Harvard, CfA) X-Ray Observations of Crab-like and Composite Supernova Remnants
- 14.10-14.40 J.A.M. Bleeker (SRON, Utrecht) Synoptic X-ray spectral study of the SMC SNRs using XMM-Newton
- 14.50-15.20 J.Hughes (Rutgers University) New Results from Magellanic Cloud SNRs

- 16.00-16.30 R.Willingale (University of Leicester, UK) SNRs to SNe - the X-ray spectroscopy connection
- 16.40-17.10 J.Vink (SRON, Utrecht) Cas A: X-ray Observations (BeppoSAX, Chandra, XMM-Newton)
- 17.20-17.50 T.Jones (University of Minnesota) Cas A: What can detailed radio, optical and X-ray comparisons reveal?

  Wednesday, Dec.10.
- 9.00-9.30 R.Petre (NASA, GSFC) New questions about young SNRs raised by recent X-ray observations
- 9.40-10.10 J.Arons (UC Berkeley) Acceleration and Dissipation in Relativistic MHD Winds
- 10.40-11.10 R.Chevalier (University of Virginia) Hydrodynamics of Supernova Remnants
- 11.20-11.50 A.M.Bykov (Ioffe Institute, St.Petersburg) Non-thermal Emission from SNRs
- 13.30-14.00 D.Ellison (North Carolina State Univ.) Hydrodynamic Simulation of Supernova Remnants Including Efficient Particle Acceleration
- 14.10-14.40 H.Tsunemi (Osaka University) Electron thermal energy in the SNR
- 14.50 - 15.20 E.Parizot (Orsay University) SNRs and Cosmic Rays
- 16.00-16.30 A.Marcowith (CESR, Toulouse) Particle transport at the SN forward shock

  Thursday, Dec.11
- Joint Discussion I:

  9.00-12.00

  What can we learn from high-resolution X-ray observations of SNRs? Impact on nuclesynthesis studies, collisionless shock physics, cosmic ray acceleration.
- Joint Discussion II:

  13.30 - 18.30

  What can we learn from high-resolution X-ray observations of SNRs? Pulsar wind nebulae.

  Friday, Dec.12
- (Pre)Supernovae Modeling and Nuclesynthesis.

- 9.00-9.30 F.-K. Thielemann (University of Basel) Nucleosynthesis Predictions for Supernovae(connections with the explosion mechanism and multi-D effects)
- 9.40-10.10 G.Meynet (Geneve Observatory) The Effects of Rotation on Presupernovae Models
- 11.00-12.00 Working Groups.
- 13.30-15.00 Working Groups
- 15.00-16.00 Concluding Remarks

5.2 "Physics of Supernova Remnants in the XMM-Newton, Chandra and INTEGRAL Era" (ISSI, Bern Sept.27 - Oct.1, 2004)

PROGRAM

Monday, Sept.27.

- 14.00-14.40 Stephen Reynolds (NCSU) Shock Acceleration in SN 1006: Still a Lot to Learn.
- 14.50-15.15 Jacco Vink (SRON, Utrecht) The non-thermal X-ray emission from RCW 86
- 15.25-15.55 Hiroshi Tsunemi (Osaka University) ASTRO-E2 prospects and its observation of the Galactic diffuse emission
- 16.20-18.00 Joint Discussion. Magnetic fields and fast particle diffusion in SNRs: What can we learn from recent observations.
- Tuesday, Sept. 28
- Gamma-Ray Studies of SNRs:
- 9.00-9.40 F.Lebrun (Saclay) & Co The INTEGRAL performance and observations
- 9.50-10.15 A.M.Bykov (Ioffe) & Co INTEGRAL view of gamma-Cyg SNR
- 10.45-12.00 Joint Discussion: Gamma-ray Observations of SNRs current status and perspectives
- 14.00-14.40 R.A.Chevalier (University of Virginia) SNR-GRB connections
- 14.50-16.00 Joint Discussion on SNR-GRB connections in a broad context including hypernovae, etc.

- 16.20-18.00 Joint Discussion on CR acceleration in SNRs and GRBs.
  Wednesday, Sept.29
- 9.00-9.40 John Raymond (CfA, Harvard) Collisionless shocks in the optical and UV: precursors and electron-ion equilibration
- 9.50-10.15 Anne Decourchelle (Saclay) Modified hydrodynamics in SNRs
- 10.25-10.55 D.C.Ellison (North Carolina State Univ.) Nonlinear Particle Acceleration at Reverse Shocks in SNRs
- 11.25-11.55 Alexandre Marcowith (CESR, Toulouse) Turbulence in collisionless SNR shocks
- 14.00-14.25 T.W.Jones (University of Minnesota) Some puzzles regarding Cas A and Kepler that come from Chandra
- 14.35- 14.55 R.A.Chevalier (University of Virginia) Type IIP supernovae and red supergiant mass loss
- 15.05- 15.30 A.M.Bykov (Ioffe Institute, St. Petersburg) On the origin of compact X-ray structures in IC 443 observed with XMM-Newton and Chandra
- 16.00-16.30 Etienne Parizot (U Orsay) Observational constraints on electron diffusion in SNRs
- 16.40-18.00 Joint Discussion Questions about SNRs raised by recent observations and X-ray observations perspective. Nucleosynthesis Predictions for Supernovae and Observations.
  Thursday, Sept.30
- 9.00-9.20 F. Bocchino (Palermo Observatory) The enigmatic X-ray halo of the plerion G21.5-0.9
- 9.30-10.10 E. van der Swaluw (FOM, Utrecht) Tracing the evolutionary stages of plerionic Supernova Remnants
- 10.40-11.10 P. Slane (CfA, Harvard) Compact Structures in Pulsar Wind Nebulae
- 11.20 - 12.00 Joint Discussion
- What can we learn from high-resolution X-ray observations of SNRs? Pulsar wind nebulae.
- 14.00-16.00 Joint Discussion High-resolution X-ray observations of SNRs. Impact on collisionless shock physics.
- 16.20-18.00 Working Groups for reviews.
  Friday, Oct.1

- 9.00-9.30 Hughes, J. (Rutgers University) A Principal Component Analysis of New Chandra Data on Tycho's Supernova Remnant
- 9.40-11.00 X-ray spectroscopy of SNR with XMM-Newton and Chandra Supernovae Modeling and Nucleosynthesis.
- 11.20-12.00 Working Groups.
- 14.00-16.00 Working Groups
- 16.00 Concluding Remarks