The Fast and the Furious: Energetic Phenomena in Isolated Neutron Stars, Pulsar Wind Nebulae & Supernova Remnants

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ABSTRACT BOOK

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Contents

Chapter 1

Invited Speakers

Review of the theory of PWNe

Niccolò Bucciantini
INAF Osservatorio di Arcetri, Italy

Pulsar Wind Nebulae (PWNe) are ideal astrophysical laboratories where high energy relativistic phenomena can be investigated. They are close, well resolved in our observations, and the knowledge derived in their study has a strong impact in many other fields, from AGNs to GRBs. Yet there are still unresolved issues, that prevent us from a full clear understanding of these objects. The lucky combination of high resolution X-ray imaging and numerical codes to handle the outflow and dynamical properties of relativistic MHD, has opened a new avenue of investigation that has lead to interesting progressed in the last years. Despite all of these, we do not understand yet how particles are accelerated, and the functioning of the pulsar wind and pulsar magnetosphere, that power PWNe. I will review what is now commonly known as the MHD paradigm. I will also review long standing problems, and future possible developments, showing how PWNe continue to provide us with new phenomenology, to challenge established ideas.

Multi-wavelength Observations of Known, and Searches for New, Gamma-ray Binaries

Robin Corbet[1], Chi Cheung[2], Malcolm Coe[3], Joel Coley[1], Davide Donato[4], Philip Edwards[5], Vanessa McBride[6], M. Virginia McSwain[7] & Jamie Stevens[5]
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We are conducting searches for new gamma-ray binaries as well as studying the small number of known systems using a multi-wavelength approach. We are hunting for new members of this rare class of objects by looking for periodic modulation of Fermi LAT light curves that would be an indication of a binary period. We have developed techniques to obtain high signal-to-noise LAT light curves and perform sensitive searches for modulation on a wide range of periods. This enabled us to discover the only completely new gamma-ray binary to be found so far with Fermi - 1FGL J1018.6-5856. Gamma-ray binaries are expected to be both radio and X-ray emitters. We therefore select sources that show possible modulation in their light curves and then conduct radio and X-ray observations to identify potential counterparts of the gamma-ray sources within the relatively large Fermi error boxes. Precise X-ray and radio positions then enable optical observations that can determine whether these are indeed new binaries. We are also conducting extended multi-wavelength observations of the known system 1FGL J1018.6-5856 to investigate how orbital modulation and other properties change at gamma-ray, radio, and X-ray wavelengths.

TeV emitting PWNe: abundant and diverse high energy engines of all ages

Arache Djannati-Atai
APC-Astroparticule et Cosmologie, Paris, France

I will discuss some of the latest discoveries and multi-wavelength investigation results on very high energy gamma-ray emitting sources associated either firmly or tentatively to pulsar wind nebulae.

Magnetar bursts at all scales

Ersin Gogus
Sabancı University

Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) form an intriguing class of slowly rotating neutron stars (also known as magnetars) which are distinguished by energetic bursts caused by their extremely strong magnetic fields (B $\sim 10^{14}$ - 10^{15} G). Magnetars undergo burst active episodes, during which they can emit anywhere from a few to thousands of energetic bursts. Bursts can broadly be classified into three groups: the typical short events, lasting for a fraction of a second, with peak luminosities (Lp) reaching up to 10^{41} erg/s, the intermediate events, having Lp $\sim 10^{42}$ - 10^{43} erg/s and the giant flares (Lp $\geq 10^{44}$ erg/s). Recently, there has been significant progress in understanding spectral properties of typical magnetar bursts, including the dimmest ones that might provide link to the underlying persistent emission. In this talk, I will give an overview of the general characteristics of magnetar bursts (including the dimmest ones), and physical mechanisms proposed to explain these energetic events.

Timing Solutions for all three Anti-Magnetars

Eric Gotthelf & Jules Halpern
Columbia Astrophysics Laboratory

We have finally obtained phase-connected timing solutions for all three known pulsars in the class of central compact objects (CCOs) in supernova remnants. These measurements now fully confirm that these young neutron stars have exceptionally weak dipole magnetic field components. For the 424 ms 1E 1207.4−5209, we resolve previous ambiguities about its spin-down rate and infer a spin-down dipole magnetic field of $Bs = 9.8 \times 10^{10}$ G, consistent with cyclotron resonance absorption at 0.7 keV and harmonics. For the 112 ms PSR J0821−4300 in Puppis A, its proper motion, $\mu = 61 \pm 9$ mas yr^{-1}, measured using Chandra, contributes a kinematic term to the Pdot via the Shklovskii effect, which subtracted yields $Bs = 2.9 \times 10^{10}$ G, similar to $Bs = 3.1 \times 10^{10}$ G determined for PSR J1852+0040 in Kes 79. Applying the antipodal model to the X-ray spectrum and pulse profiles of PSR J0821-4300, we deduce the surface hot and warm spot temperatures and areas. Paradoxically, such nonuniform surface temperature require strong crustal magnetic fields, probably toroidal or quadrupolar components much stronger than the external dipole. A spectral line feature at either, 0.75 keV in emission or 0.46 keV in absorption, is modulated with rotation, possibly due to a cyclotron process in a magnetic field on the surface. These results deepen the mystery of the origin and evolution of CCOs: why are their numerous descendants not evident?

The Magnificent Seven: Nearby, Thermally Emitting, Isolated Neutron Stars

Frank Haberl
Max Planck Institute for extraterrestrial Physics, Garching, Germany

The ROSAT all-sky survey revealed seven isolated neutron stars with predominantly thermal X-ray emission which are often called the "Magnificent Seven" (M7). Despite extensive searches only few much fainter candidates were found since then. Over the last years the outstanding capabilities of the X-ray observatories XMM-Newton and Chandra with respect to sensitivity and spectral resolution increased our knowledge about the M7 considerably. For all seven, X-ray pulsations have been found in the range 3 to 12 s. Measurements of their spin down rates and kinematic estimates for their ages suggest that the M7 are of the order of a few 100 thousand to one million years old. Thermal emission with temperatures of about 0.3-1 million K dominates the X-ray spectra of the M7 and no non-thermal activity is seen. This offers the unique opportunity to investigate their relatively undisturbed thermal emission in X-rays which has provided crucial insights on their surface temperature and magnetic field distributions. The results are essential to derive important information on the structure and chemical composition of the neutron star surface layers.

X-ray observations of pulsar-wind nebulae: current status and future prospects

Oleg Kargaltsev[1], George Pavlov[2] & Martin Durant[3]
[1] *George Washington University*
[2] *Pennsylvania State University*
[3] *University of Toronto*

The modern X-ray observatories have significantly advanced our understanding of pulsar winds and pulsar wind nebulae (PWNe) in many aspects. Deep, high-resolution imaging reveals the fine structure of pulsar winds - termination shocks in the equatorial wind, polar jets with moving knots, and more complex structures on different scales. The spatially resolved spectroscopy allows measurements of the particle injection spectrum in the vicinity of the termination shock and enables investigation of the spectral evolution as a function of distance from the pulsar. Finally, repeating observations of the same PWNe have demonstrated that the pulsar wind nebulae are highly variable on various timescales. I will review most recent interesting results including cork-screw motion of the Vela jet, first binary PWN resolved in X-rays, spectral maps for a number of bright PWNe, possible extended emission around magnetars, structure of the bow-shock nebulae, and long pulsar tails. I will also discuss future prospects of pulsar wind observations in X-rays.

Gamma-ray emission of Crab pulsar and the nebula

Maxim Lyutikov
Purdue University

We discuss growing evidence that pulsar high energy emission is generated via Inverse Compton mechanism. We reproduce the broadband spectrum of Crab pulsar, from UV to very high energy gamma-rays - nearly ten decades in energy, within the framework of the cyclotron-self-Compton model.

Secondly, recent observations of flares in the Crab nebula call into question the prevalent model of particle acceleration in relativistic astrophysical environments, the stochastic shock acceleration. Magnetic reconnection is likely to play an important, and perhaps a dominant role.

X-ray observations of rotation-powered pulsars

George Pavlov[1], Oleg Kargaltsev[2], Bettina Posselt[1] & Martin Durant[3]
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[2] *George Washington University, Washington DC, USA*
[3] *University of Toronto, Toronto, Canada*

Radiation of most of the known pulsars is powered by the loss of their rotational energy. Thanks to the XMM-Newton and Chandra, X-ray emission has been detected from over 100 rotation-powered pulsars. I will overview the current results of X-ray observations of rotation-powered pulsars, including thermal and magnetospheric components of X-ray emission, evolution of the X-ray properties, connection between the X-ray emission and emission at other wavelengths, and various implications of the observational results.

Magneto-thermal evolution of strongly magnetized neutron stars.

Jose Pons
University of Alicante

Magnetars are believed to be powered by ultra-strong magnetic fields but their diversity of observed behaviors is not well understood. This has become even more puzzling after the discovery of "low-field" magnetars. By performing long-term two-dimensional simulations of the coupled magnetic, thermal, and rotational evolution of neutron stars, we try to establish evolutionary links between the (apparently different) observational classes. With this approach we can also estimate the evolution of magnetic stresses in the crust, which allows us to establish when starquakes occur. From our results, we can give a qualitative description of the main stages in the evolution of a neutron star, from its youth to its old age, and connect them with observations.

Magnetars: explosive neutron stars with extreme magnetic fields

Nanda Rea
CSIC-IEEC, Barcelona, Spain

The properties of matter under the influence of magnetic fields and the role of electromagnetism in physical processes are key areas of research in physics, biology, bioengineering, chemistry, geology and many other branches of science. However, despite decades of research, our ignorance of many physical processes related with strong magnetic fields is clear: to test our theoretical predictions for new physical processes and the state of matter under the most extreme magnetic conditions, we have only one possibility: we need to turn to astronomical observations. Among the many different classes of stellar objects, neutron stars provide a unique environment where we can test (at the same time) our understanding of matter with extreme density, temperature, and magnetic field. In this more general contest, I will review our current knowledge on the most magnetic objects in the Universe, a small sample of neutron stars called magnetars. The study of the powerful high-energy emission, and the flares from these strongly magnetized (10^{15} Gauss) neutron stars is providing crucial information about the physics involved at these extremes conditions, reserving us many unexpected surprises.

Gamma-ray Pulsars with the Fermi Satellite

David Smith
Centre d'Études Nucléaires de Bordeaux-Gradignan, CNRS/IN2P3, France

The Large Area Telescope (LAT) on NASA's Fermi satellite sees gamma-ray pulsations from over 125 pulsars: the largest class of GeV sources in the Milky Way. Over 50 emit non-thermal X-ray radiation. Over a third are millisecond pulsars, widespread in Galactic latitude, many of which show the effects of the companion star's intense wind ("black widows"). The rest are young pulsars, divided evenly between radio-loud and radio-quiet. Several reside in GeV pulsar wind nebulae. The distributions of spectral and pulse profile shapes indicate emission regions high above the neutron star surface, towards the light cylinder. I will summarize the properties of the gamma-ray pulsars, highlighting insights that the tallies provide.

Suzaku Observations of Gamma-Ray Binaries and Prospects for ASTRO-H

Takaaki Tanaka
Kyoto University, Kyoto, Japan

Recent TeV and GeV gamma-ray observations revealed that some X-ray binaries are loud also in the gamma-ray band, providing evidence for particle acceleration in those objects up to high energies or very high energies. They constitute a new category of X-ray binaries, called gamma-ray binaries. For most of them, it is not yet clear whether their compact objects are neutron stars or black holes, which makes it difficult to disentangle possible scenarios to explain the observations. The X-ray band is one of the key energy bands to study gamma-ray binaries. The Suzaku satellite so far observed gamma-ray binaries such as LS 5039, LS I +61°303, PSR B1259−63, HESS J0632+057, and recently 1FGL J1018.6−5856. Generally, X-ray spectra of gamma-ray binaries are power-law like, and, therefore, Suzaku is suitable for studying them with its low background level and wide band coverage. In this talk, we will summarize Suzaku results on gamma-ray binaries and discuss their implication for emission mechanisms and particle acceleration. We will also mention prospects for the successor of Suzaku, ASTRO-H, which will be launched in 2015.

The Flaring Crab Nebula: Surprises and Challenges

Marco Tavani
INAF-IAPS, Rome, Italy

The Crab Nebula, the "Queen of Nebulae", continues to surprise us. The discovery in 2010 by AGILE and the Fermi confirmation of transient gamma-ray emission from the Crab shattered the paradigm of quasi-steady nebular emission. Several episodes of enhanced gamma-ray emission above 100 MeV have been detected from the Crab with timescales ranging from hours to weeks and a broad variety of peak fluxes. Having excluded the presence of a nearby extra source or pulsar activity, the transient emission is attributed to the Nebula.

We will discuss the most prominent transient gamma-ray episodes with emphasis on the recent attempts to identifying the flaring location(s) in the Nebula. We will then address the theoretical challenge of what can be called a mechanism of "super-acceleration". This mechanism is acting on very short timescales (hours) in the Crab, and implies a drastic modification of MHD-based diffusive particle acceleration mechanisms. The phenomenon can be related with plasma instabilities and magnetic field reconnection episodes under specific conditions (but a demonstration is challenging). What is certain is that the Crab provides a unique laboratory to study extreme acceleration phenomena.

High-energy pulsar models: Developments and new questions

Christo Venter[1] & Alice K. Harding[2]
[1] *Centre for Space Research, North-West University, Potchefstroom, South Africa*
[2] *Astrophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*

There has been a major advance in observational knowledge of high-energy (HE) pulsars. Fermi and Agile have detected over 100 HE pulsars, with roughly equal numbers being millisecond pulsars (MSPs), young radio-loud, and young radio-quiet pulsars. The wealth of new data have stimulated further pulsar model development. Geometric light curve modelling has uncovered three pulsar classes the radio profile either precedes, trails, or is aligned with the gamma-ray one. These models imply outer-magnetospheric emission, indicating copious pair production even in low-power MSP magnetospheres. New global magnetosphere models specifying finite conductivity on field lines above the stellar surface are filling the gap between the standard vacuum vs. plasma-filled models. Phase-resolved spectra, coupled with the sizable HE pulsar population that allow sampling of various geometries, will enable stringent testing of radiation models. Reproduction of the phase-resolved behaviour will be one of the next frontiers in pulsar science, impacting on our understanding of particle acceleration, emission, and magnetosphere geometry. One may now also study evolutionary trends and probe several visibility and population synthesis questions. The recent detection of sub-TeV pulsations from the Crab stimulated ideas to extend the standard models, possibly even bridging pulsar and pulsar wind nebula physics.

Large Observatory for X-ray Timing (LOFT)

M. van der Klis[1] on behalf of the LOFT Consortium
[1] *University of Amsterdam*

LOFT, the Large Observatory For X-ray Timing, is an X-ray space mission designed to answer fundamental questions about the general relativistic motion of matter orbiting close to the event horizon of a black hole, and the equation of state of matter in neutron stars. It comprises a collimated 2-30 keV, 260 eV resolution Si X-ray detector with an effective area of 10 m^2 and and a coded mask wide field monitor based on the same detector technology with a 2.1 mCrab detection sensitivity (1 day elapsed, 5 sigma, Galactic Center). With a focus on the properties of dense matter and strong field gravity in accreting compact objects, clearly the opportunities for a large variety of investigations with this mission are tremendous and these are explicitly part of the LOFT observation plan. LOFT was selected by ESA as one of the four space mission concepts of the Cosmic Vision programme that (with an addtional fifth mission) will compete for a launch opportunity in the early 2020s.

Chapter 2

High-energy emission from rotation-powered neutron stars

2D Particle-in-Cell Simulation of the Pulsar Polar-cap Discharge

Alexander Yuran Chen & Andrei Beloborodov
Columbia University

We developed a 2D particle-in-cell (PIC) code to simulate highly relativistic dense plasma with electron-positron pair creation through inverse compton scattering and curvature radiation. We are applying the code to the polar cap of the neutron star to investigate the charge acceleration mechanism, how the gap is formed, and how pair creation is maintained at the polar cap. The main focus of the study is on the interplay between the polar cap discharge region and the global magnetosphere. Here we are presenting some of the preliminary results that we find through the simulation.

Multi-component X-ray Spectral Analysis of the Double Pulsar System J0737-3039

Elise Egron, Alberto Pellizzoni & Maria Noemi Iacolina
INAF - OAC, Cagliari, Italy

Discovered in 2003, PSR J0737-3039 represents a rare and amazing system since two radio pulsars are orbiting each other. The high-energy study of such system is extremely interesting to understand the physics of the magnetospheric emissions/interactions of both neutron stars.

We present the results of the spectral analysis of the 230 ks jointly with the 360 ks large-program observations performed by XMM-Newton in 2006 and 2011, respectively, using the EPIC-PN, MOS1 and MOS2 data. Multi-component models are required to properly account for the magnetospheric and surface emission from both pulsars and their interactions. Different possibilities are discussed in the frame of the multiwavelength puzzling model of the Double Pulsar.

XMM-Newton revealed synchronous X-ray and radio mode changing in a pulsar: a bi-stable emission behaviour requiring global magnetospheric changes

Wim Hermsen
SRON Netherlands Institute for Space Research, Utrecht, The Netherlands

Pulsars are unique electromagnetic generators, capable of producing emission from low-frequency radio waves up to high-energy gamma rays. This emission can be generated anywhere from the surface of the pulsar out to the edges of its magnetosphere. There is still no consensus on the production scenarios, 45 years after their discovery. In their radio emission, many pulsars exhibit mode switching, instantaneously changing pulse shape, intensity and sub-pulse drifting. Also for this bi-stable emission behavior the mechanism is not understood. In this talk I will present simultaneous observations with the XMM-Newton, LOFAR and GMRT telescopes of the mode-switching pulsar PSR B0943+10. Most surprisingly, this X-ray-radio campaign revealed synchronous switching in the radio and X-ray emission properties, challenging all proposed pulsar emission models and suggesting an interpretation with rapid, global changes to the conditions in the entire magnetosphere. The XMM-Newton observations were key to this discovery and a new campaign is approved on a twin of PSR B0943+10, namely PSR B1822-09. These pulsars show very similar radio-mode-switching characteristics, but the first is an almost aligned and the second an orthogonal rotator. This geometric difference and different viewing angles might allow us to uncover the mechanism behind this enigmatic behavior.

New Fermi-LAT Gamma-ray Pulsars Using Radio Ephemerides

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[1] *Centre d'Études Nucléaires de Bordeaux-Gradignan, CNRS/IN2P3, France*
[2] *For the Fermi LAT Collaboration and the Pulsar Timing Consortium*

Gamma-ray pulsations from more than 145 pulsars (March 2013) have been detected with the Large Area Telescope (LAT) on board the Fermi satellite since June 2008. Of these, 125 are listed at

https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

which encompasses 117 objects detailed in the Second Fermi-LAT Catalog of Gamma-ray Pulsars and 8 more pulsars found after the completion of the catalog. Analysis and publication of new LAT pulsars is ongoing. Pulsation Search Using Ephemerides (PSUE) of known radio/X-ray pulsars has been an efficient method and has permitted more than 88 detections. The rest are discovered either by blind period searches of the gamma-ray data or through deep radio observations of unidentified LAT sources. We report here the discovery of several of the new PSUE gamma-ray pulsars and characterize their light curves and spectral properties.

Long Term X-Ray Timing of the Double Pulsar PSR J0737-3039

Maria Noemi Iacolina[1], Alberto Pellizzoni[1], Elise Egron[1] & Paolo Esposito[2]
[1]*INAF - OAC Cagliari, Italy*
[2]*INAF - IASF Milano, Italy*

The relativistic double neutron star binary PSR J0737-3039 is a truly unique system offering the diagnostics of two interacting radio pulsars in a short orbital period system. Clear evidences of orbital phase-dependent interactions between the two neutron stars are seen both in radio and X-rays observations.

We present the timing analysis results of the PSR J0737-3039 observations performed in the context of the 2006 and 2011 XMM-Newton Large programs providing $\sim$20000 X-ray counts overall from the system. Despite no significant orbital flux variability is detected, both pulsars of the system are seen in X-ray providing physical insights on the physics of the mutual interactions in their close environment. In particular, we discuss possible processes behind the peculiar X-ray brightening of the "lazy pulsar" PSR B via energy transfer from the "power plant" PSR A.

Particle acceleration region of old pulsars

Shota Kisaka & Shuta Tanaka
Institute for Cosmic Ray Research, University of Tokyo, Chiba, Japan

Recently, the number of old pulsars (> 1Myr) detected in X-ray observations has increased. We constrain the particle acceleration and pair creation regions of old pulsars based on these observational results. We assume that the mechanism of non-thermal X-ray emission is synchrotron radiation. We find that the emission region locate $10 - 100$ times the stellar radius, which corresponds to $\sim 10^{-2}$ times the light cylinder radius. In this region, the number density of the created pairs is much smaller than the Goldreich-Julian one. Because the pair creation rate is not enough to maintain the sustainability of the acceleration gap, our results implicate the quasi-periodic behavior across the broad region in old pulsar magnetospheres.

The soft gamma-ray pulsar population and its link to the Fermi LAT pulsar population: a full high-energy picture

Lucien Kuiper[1] & Wim Hermsen[2]
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[2] *Astronomical Institute "Anton Pannekoek", University of Amsterdam*

While at high-energy gamma-rays (>100 MeV) the Fermi LAT already detected more than 120 pulsars since its launch in June 2008, the number of pulsars seen at soft gamma-rays (20 keV - 30 MeV) is still very limited, though steadily growing.

Namely, in recent years targeted deep radio and/or X-ray observations of Supernova remnants, TeV sources and newly discovered INTEGRAL sources revealed the presence of young and energetic pulsars, surrounded by bright pulsar wind nebulae (PWN).

Currently, the total number of detected soft gamma-ray pulsars counts 16 secure members. The average characteristics of these soft gamma-ray pulsars differ from those of the LAT detected pulsars, e.g. the Fermi LAT pulsar population typically reaches its peak luminosity at GeV energies, the soft gamma-ray pulsar population does so at MeV energies. In this presentation I will discuss the characteristics of this soft gamma-ray pulsar population in comparison with the Fermi LAT findings in order to obtain a full high-energy picture of the pulsar population.

Deep X-ray Observations of the High-Magnetic-Field Radio Pulsar J1119-6127

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[7] *University of British Columbia*

High-magnetic-field radio pulsars are important transition objects for understanding the connection between magnetars and conventional radio pulsars. We present an X-ray study of the young high-B pulsar J1119-6127 using deep XMM-Newton and Chandra observations. The pulsar emission shows strong modulation below 2.5keV, with a single-peaked profile that can be produced by a single hot spot on surface. This could be the result of anisotropic heat conduction under a strong magnetic field, and a single-peaked profile seems common among high-B radio pulsars. For the associated remnant G292.2-0.5, its large diameter could be attributed to fast expansion in a low-density wind cavity, likely formed by a Wolf-Rayet progenitor. This is similar to two other high-B radio pulsars, seemingly suggesting a possible link between progenitor mass and neutron star B-fields.

A unified polar cap/striped wind model for pulsed radio and gamma-ray emission in pulsars

Jérôme Pétri
Observatoire Astronomique de Strasbourg

The recent discovery by Fermi of more than one hundred new gamma-ray pulsars makes it possible to look for statistical properties of their pulsed high-energy emission. These pulsars emit by definition mostly gamma-ray photons but some of them are also detected in the radio band. For the latter, the relation between time lag of radio/gamma-ray pulses and gamma-ray peak separation helps to put some constraints on the magnetospheric emission mechanisms and location. This idea is analyzed in detail, assuming a polar cap model for the radio pulses and the striped wind geometry for the high-energy counterpart. Combining the time-dependent emissivity in the wind with a simple polar cap emission model, we compute the radio and gamma-ray light-curves. The phase lag as well as the gamma-ray peak separation dependence on the pulsar inclination angle and on the viewing angle are studied and compared with available observations. The gamma-ray luminosity from synchrotron emission in the wind is also discussed.

Plasma-producing Gaps in the Global Structure of the Pulsar Force-free Magnetosphere

Svetlana Petrova
Institute of Radio Astronomy, Kharkov, Ukraine

The pulsar high-energy emission is usually associated with the magnetospheric gaps, which are traditionally considered within the framework of the vacuum dipole model of the magnetosphere. Actually the presence of an abundant plasma should modify the magnetospheric structure, and the context of the force-free magnetosphere, where the electromagnetic forces are balanced over most part of the volume, is more appropriate. We present a semi-empirical model of the pulsar force-free magnetosphere, which for the first time includes the polar, outer and slot gaps. The gaps not only supply the magnetosphere with plasma, but also determine the actual boundary conditions of the force-free problem. Moreover, the gaps may play an important role in sustaining and closing the pulsar current circuit. Proceeding from the generalized multipolar solution of the pulsar equation, we suggest the split-offset monopole scheme, which, as opposed to the classical split monopole, better replicates the field of a force-free dipole beyond the light cylinder, allowing for the consequences of the gap presence in the magnetosphere. The first results as to the analytical description of the pulsar magnetosphere based on our model will be presented, and the implications of the model will be discussed.

Physical links between the radio and high-energy emissions of pulsars

Svetlana Petrova
Institute of Radio Astronomy, Kharkov, Ukraine

The radio photon reprocessing by the relativistically gyrating plasma particles in the open field line tube of a pulsar is considered. The particle relativistic gyration results from the resonant absorption of radio photons in the outer magnetosphere. The spontaneous synchrotron re-emission of the particles falls into the optical and soft X-ray ranges and thus contributes to the non-thermal high-energy emission of a pulsar. The radio photon scattering off the relativistically gyrating particles also deposits photons into the high-energy range. Both processes can underlie the potentially observable features of the radio-high energy connection in pulsars and, in particular, account for the manifestations already observed in the Crab and Vela pulsars. In the framework of our theory, the strongest correlation is expected for the low-frequency radio photons.

Probing the cooling of the Central Compact Object in the Cas A supernova remnant

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A 4 percent decline in the surface temperature and a 21 percent decline in the X-ray flux over a time span of 9 years has been reported by Heinke & Ho 2010 for the Cas A CCO, which is likely a neutron star with a low magnetic field. The rapid cooling has interesting implications for the composition and properties of the neutron star interior. However, the bright CCO suffered from a strong pile-up in most of the previously investigated Chandra ACIS observations which introduced an additional uncertainty in the data analysis.

We will present a detailed analysis of two Chandra ACIS observations of the Cas A CCO, taken in 2006 and 2012 in exactly the same instrumental setup, with negligible pile-up. We will assess the effect of various factors on the inferred changes of the temperature and other spectral parameters, including the neutron star atmosphere model used in the spectral fit, the variable absorption in the SNR, and the varying contamination of the ACIS detector. As a result, we do not see a significant temperature change between 2006 and 2012, and we will discuss the respective constraints from our analysis.

X-ray observations and the search for Fermi-LAT gamma-ray pulsars

Pablo Saz Parkinson[1], Andrea Belfiore[1], Patrizia Caraveo[2], Andrea De Luca[2] & Martino Marelli[2]
[1]*SCIPP, University of California, Santa Cruz, USA*
[2]*INAF-IASF, Milano, Italy*

The Large Area Telescope (LAT) on Fermi has detected over 125 gamma-ray pulsars, about a third of which were found in blind searches of the gamma-ray data. Because the angular resolution of the LAT is relatively poor and blind searches for pulsars (especially those for millisecond pulsars) are very sensitive to the position used in the search, one must scan large numbers of locations. Identifying a small number of plausible X-ray counterparts can drastically reduce the number of trials in position and thus improve the sensitivity of pulsar blind searches with the LAT. I will discuss our ongoing program of XMM, Chandra, and Swift observations of Fermi-LAT sources and describe how these observations enable sensitive blind searches for pulsations. I will also summarize the latest results of these searches.

Spectral properties and HE behaviour of few bright and young Fermi PSRs

Thomas Tavernier
APC, Paris Diderot

The discovery of pulsars is more than 40 years old and we are far from understanding these fascinating objects. The number of detected pulsars at high energy has known great progress since the launch of the Fermi satellite in 2008, and this number is still growing.

If the mechanisms behind the non-thermal radiation of pulsars (synchrotron, curvature radiation or inverse Compton) are well known, the details of these processes remain widely debated through several models. Four years after the launch of Fermi, the study of the spectral behaviour of the brightest pulsars reveals for some individuals, a softer cut-off at high energies than expected in most models. Moreover, the detection of the Crab PSR in the 100-500 GeV range by the VERITAS and MAGIC collaborations have paved the way for the VHE studie of young pulsars.

These first results allow us to ask questions about the validity of the existing models, but also to look at prospects for current and next generation Cherenkov telescope systems.

Soft Gamma-ray Pulsars

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We propose a model to explain the X-ray and soft gamma-ray spectra and light curves of a class of young pulsars, PSR B1509-58, PSR J1846-0258, PSR J1811-1925, PSR J1617-5055 and PSR J1930+1852. These five spin-down powered pulsars have similar shapes of pulse profiles and spectra of non-thermal X-ray, which can be described by power law with photon index around 1.2. None of them has multi-GeV photon detected. In the outer gap model, most pairs inside the gap are created around the null charge surface and the gap's electric field separates the two charges to move in opposite directions. Consequently, the region from the null charge surface to the light cylinder is dominated by the outflow of particles and that from the null charge surface to the star is dominated by the inflow of particles. These particles emit curvature photons, and the incoming curvature photons are converted by the strong magnetic field of the neutron star to pairs. We suggest that the outgoing curvature photons of the five pulsars are missed by the lines of sight, and the X-rays and soft gamma-rays of them are the synchrotron radiation of the pairs generated by the magnetic field.

Chapter 3

Multiwavelength properties and unification scenarios for different classes of neutron stars

Fermi-LAT observations and a broadband study of supernova remnant CTB 109

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CTB 109 (G109.1-1.0) is a Galactic supernova remnant (SNR) with a hemispherical shell morphology in X-rays and in the radio band. We report the detection of gamma-ray emission coincident with this SNR, using data from the Fermi Large Area Telescope (Fermi-LAT), and we present a study of the broadband characteristics of the remnant using a model that includes hydrodynamics, efficient cosmic ray acceleration, nonthermal emission and a self-consistent calculation of the X-ray thermal emission. We find that the observations can be successfully fit with two distinct parameter sets, one where the gamma-ray emission is produced primarily by leptons accelerated at the SNR forward shock and the other where gamma-rays produced by forward shock accelerated cosmic-ray ions dominate the high-energy emission. Consideration of thermal X-ray emission introduces a novel element to the broadband fitting process, and while it does not rule out either the leptonic or the hadronic scenarios, it constrains the parameter sets required by the model to fit the observations. Additionally, we consider possible gamma-ray emission from the anomalous X-ray pulsar (AXP) 1E 2259+586, located at approximately the center of curvature of the SNR shell.

Constraining Magnetar Bursts Properties from Energy-Dependent Variability

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Soft gamma-ray repeaters are characterized by outbursts of activity (typically lasting days to months) with enhanced persistent emission and a series of short ($\sim$0.1 s) X-ray/gamma-ray bursts. The spectrum of these bursts can be equivalently fit with models with very different physical properties, making it difficult to constrain the underlying burst mechanism. We demonstrate how the energy-dependent timing properties of the bursts can provide new constraints on theoretical emission models and the flare process. The discussion will focus on the 2008/2009 outburst of the magnetar SGR J1550-5418 (also known as 1E 1547-5408 and PSR J1550-5418) and compare its variability properties to similar outbursts from SGR 1806-20 and SGR 1900+14.

The first complete X-ray view of the Supernova Remnant Puppis A

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The supernova remnant (SNR) Puppis A, a source that includes the central compact object RX J0822-4300, relics of the precursor star and traces of the interaction between the SN shock and the dense surrounding gas, has been extensively studied from radio to GeV gamma-rays. However, the existing X-ray images surprisingly lack a considerable portion of the source towards the south and southwest.

We report the first detailed full view of Puppis A in X-rays (with images in the 0.3-0.7, 0.7-1.0 and 1.0-8.0 keV bands) based on the combination of new XMM-Newton observations with existing XMM-Newton and Chandra data. From these images we investigate in detail the SNR morphology, carry out multiwavelength comparisons and estimate the flux density and luminosity of the whole SNR. We have also collected and updated the broad-band data of Puppis A across the whole electromagnetic spectrum, producing the Spectral Energy Distribution (SED) and re-analyzed radio data to estimate the minimum energy stored in relativistic particles, as well as the magnetic field strength, useful parameters to set constraints on the mechanisms that give origin to the high-energy emission.

Suzaku View of Recent Magnetar and Magnetar-related Objects

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Almost all the magnetars are bright in soft X-rays below 10 keV, characterized as a thermal emission, $kT \sim 0.5$ keV, from the stellar surface. Some brighter ones further exhibit another hard X-ray component above 10 keV, extending at least up to 100 keV or more with an extremely hard photon index, $\Gamma \sim 1$. Thanks to its wide-band coverage, 0.5–600 keV, the Suzaku X-ray satellite simultaneously observed two components, and suggested, based on the 2009 data, the broadband spectral ratio between them is correlated with their magnetic field and characteristic age. This implies a possible spectral unification of the magnetar class. At the end of AO-7 in 2012, Suzaku completed observation of 13 sources among 17 magnetars in our Galaxy, which exceeds the critical field 4.4×10^{13} G. We will review these recent Suzaku analyses on the magnetar class, including ToO observations followed by further monitoring AO observations performed one or two year later from the activation. We will also introduce some magnetar-related objects, such as possible highly magnetized pulsars in the binary systems.

Modulating magnetar emission by magneto-elastic oscillations

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Our numerical simulations show that axisymmetric, torsional, magneto-elastic oscillations of magnetars including a superfluid core can explain the whole range of observed quasi-periodic oscillations (QPOs) in the giant flares of soft gamma-ray repeaters. There exist constant phase, magneto-elastic QPOs at both low ($f < 150$ Hz) and high frequencies ($f > 500$ Hz), in full agreement with observations. The range of magnetic field strengths necessary to match the observed QPO frequencies agrees with the spin-down estimates. These results strongly suggest that neutrons in magnetar cores are superfluid.

These oscillations of the magnetar can modulate the electro-magnetic emission by resonant cyclotron scattering (RCS). We present a new code to calculate the RCS in the magnetoshpere of magnetars. It includes: i) a consistent calculation of the magnetic field; ii) a Monte-Carlo approach for the relativistic radiation transport of the photons that is employing the QED-corrected cross sections for the RCS; iii) a consistent calculation of the momentum distribution of the currents in the magnetosphere induced by the twisted magnetic field.

The Progenitor and Pulsar Birth Properties of Composite SNR Kes 75

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It is possible to infer the birth properties of a pulsar wind nebulae and the properties (mass, initial kinetic energy) of material ejected in the progenitor supernova by modeling the observed properties of a pulsar wind nebulae inside a supernova remnant. In this talk, I present the results of such modeling for Kes 75, which is of particular interest since the spin-down properties of its associate pulsar suggests a magnetar-strength dipole surface magnetic field, and this neutron star exhibited magnetar-like X-ray flares only a few years ago. The initial spin period estimated for this neutron star, and the progenitor properties inferred from the estimate supernova ejecta mass and energy, allow us to test theories for magnetar formation. In this talk, I will present our initial results from this analysis.

Observationally consistent evolution scenario for neutron stars in LMXBs

Mikhail Gusakov, Andrey Chugunov & Elena Kantor
Ioffe Institute, St.-Petersburg, Russia

A scenario which explains the existence of rapidly rotating warm neutron stars in LMXBs is suggested. It is based on the idea of resonance interaction of normal r-modes with superfluid modes (see the presentation 'New instability windows for rotating neutron stars' by Gusakov, Chugunov & Kantor for details). We perform detailed simulations of neutron star evolution in LMXBs for a wide set of parameters and demonstrate that neutron star rotation frequency is limited by the instability of $m = 3$ r-mode rather than $m = 2$ r-mode, as is usually believed. This result agrees with the predicted value of the cutoff spin frequency ~ 730 Hz, derived from statistical analysis of the accreting millisecond X-ray pulsars. The scenario allows us to explain all rapidly rotating neutron stars observed in LMXBs, as well as the existence of millisecond pulsars. Confronting our scenario with observations opens a new possibility to put stringent constraints on the properties of superdense matter.

This study was supported by RF Presidential Programme (grants MK-857.2012.2 and NSh-4035.2012.2), RFBR (grants 11-02-00253-a and 12-02-31270-mol-a), and by Ministry of Education and Science of Russian Federation (Agreement No. 8409, 2012).

New instability windows for rotating neutron stars

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We reanalyze the r-mode instability in rotating superfluid neutron stars. To this aim we develop a model of resonance interaction of normal $m = 2$ r-mode with superfluid modes. We show that this interaction dramatically modifies the instability window, that is the region of stellar spin frequencies and temperatures in which a neutron star becomes unstable with respect to radiation of gravitational waves. This modification allows us to formulate an evolution scenario for neutron stars in LMXBs that can explain all rapidly rotating neutron stars observed in LMXBs, as well as the existence of millisecond pulsars (see the presentation 'Observationally consistent evolution scenario for neutron stars in LMXBs' by Gusakov, Chugunov, & Kantor).

This study was supported by RF Presidential Programme (grants MK-857.2012.2 and NSh-4035.2012.2), RFBR (grants 11-02-00253-a and 12-02-31270-mol-a), and by Ministry of Education and Science of Russian Federation (Agreement No. 8409, 2012).

Hard X-ray emission from magnetars: fit by a physical model and resulting constraints

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We test a recently proposed model for persistent hard X-ray emission from magnetars. In the model, hard X-rays are produced by a relativistic electron-positron outflow in the closed twisted magnetosphere. The outflow decelerates as it radiates its energy away via resonant scattering of soft X-rays, reaches the top of the magnetic loop and annihilates there. The emitted spectrum is controlled by the Lorentz factor of the decelerating flow, which is self-consistently calculated. We test the model against observations of 4U 0141+61 and 1RXS J170849-400910 by INTEGRAL, RXTE, XMM-Newton, and ASCA. We find that the model successfully fits the observed phase-resolved spectra. We derive constraints on the angle between the rotational and magnetic axes of the neutron star, its magnetic dipole moment, the object inclination to the line of sight, and the size of the active twisted region filled with the plasma flow. We also discuss the thermal and nonthermal soft X-ray components of the emission spectrum.

Magnetic fields decay in pulsars: population synthesis and other statistical methods

Andrei Igoshev
Sobolev Institute of Astronomy, Saint Petersburg State University

The magnetic field decay in pulsars and its influence on the pulsar ensemble are the open questions since the physical mechanism of the braking was revealed. The magnetic field decay was studied by means of different techniques such as kinematic equation, the population synthesis method and some statistical models (e.g. Igoshev 2012). In this talk we compare these approaches and show how they are sensitive and how statistically significant are their results. We also present the restored magnetic field decay law from the study by Igoshev (2012). The method described in that article restores magnetic field decay law basing on the distribution of pulsars by spin-down ages. This method is tested by means of the population synthesis. Samples generated with different sets of assumptions are analyzed by the method and it is shown that one is sensitive and its results are statistically significant. We also discuss what individual kinematic ages from the study by Noutsos et al. (2013) can give for the problem of magnetic field decay.

Deep observations of PSR J0357+3205 with GTC

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The new middle-aged (0.5 Myr) γ-ray pulsar J0357+3205 was recently discovered with Fermi. Standard cooling theory which assumes the modified Urca processes as the main neutrino emission mechanism predicts T $\sim$ 35–50 eV for neutron stars (NSs) of this age. However, subsequent Chandra and XMM-Newton X-ray observations showed only thermal emission from a hot spot plus non-thermal power-law component and no thermal emission from the entire surface of the NS with the surface temperature upper limit of about 30 eV. We present deep observations of PSR J0357+3205 in SDSS-g' filter performed with 10-m GTC (Gran Telescopio Canarias). We haven't detected any source at the pulsar position up to 28.5 magnitude, which is much below the level expected from extrapolation of the X-ray non-thermal component. This also yields the same 30 eV constraint on the NS surface temperature as provided by the X-ray data, which means that rapid cooling mechanisms likely operate within the NS. Future observations of the pulsar in UV can provide more stringent constraints.

On the X-ray emission mechanisms of the persistent source and very low-fluence bursts of SGR J0501+4516

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In this talk I will present a detailed spectral study of the X-ray emission of the persistent source and the low-fluence bursts of SGR J0501+4516 observed during a 50 ks XMM-Newton observation near the peak of its 2008 outburst. For the persistent emission we employ a physically motivated continuum emission model and spectroscopically determine important source parameters; such as, the surface magnetic field strength and the magnetospheric scattering optical depth. We find that the surface temperature near the peak of its activity is 0.38 keV, yielding an emitting area of 131 km^2 at a distance of 2 kpc.. The surface magnetic field strength determined spectroscopically, $B=2.2 \times 10^{14}$ G, is consistent with the dipole field strength inferred from the source spin and spin down rate. We fit the stacked spectra of 129 very faint bursts with a magnetospheric scattered modified blackbody model and find a temperature of 1.16 keV, corresponding to an emission area of 93 km^2. We also find an evidence for cooling during the burst decay phase.

New XMM-Newton observation of the thermally emitting isolated neutron star in the Carina Nebula

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2XMM J104608.7-594306 is a thermally emitting isolated neutron star (INS) sharing many of the properties of the intriguing Magnificent Seven (M7), namely a thermal spectrum with broad absorption lines, no magnetospheric emission and lack of optical, radio or gamma-ray counterparts. While the M7 rotate with periods of few seconds, we found intriguing evidence for a very fast spin of 19 ms in a dedicated XMM-Newton observation of the source conducted in 2010. The fast rotation period, purely thermal X-ray spectrum and presence in the Carina Nebula (which excludes an old and fully-recycled pulsar) make this neutron star unique amongst the currently known INS population. In this contribution, while discussing the properties of peculiar neutron stars and possible missing links, we will present results of a second XMM-Newton observation of the source. The new data, aimed at confirming the candidate spin and the presence of spectral absorption lines, could potentially constrain the spin-down rate of the source, therefore its magnetic field and evolutionary state.

Supernova Remnants with Magnetars

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Supernova Remnants (SNR) are the reminiscence of a SN explosion of a massive star. Sometimes, the nucleus of this progenitor star survives as a neutron star or a black hole. In the recent years, a new class of highly magnetized neutrons stars (10^{14}-10^{15} G) has been discovered, the so-called magnetars. The mechanism of formation of these magnetars is still under debate. In this talk, I will present spectroscopic analysis of three magnetars in SNRs (Kes 73, CTB 109 and N 49) using *XMM-Newton* data. I will compare them with other SNRs. Also, we search for correlations and trends between SNRs with magnetar and with normal pulsars using the X-ray photometric data available in the literature.

The shape of the cutoff in the synchrotron emission of SN 1006 observed with XMM-Newton

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Synchrotron X-ray emission from the rims of young supernova remnants allows us to study the high-energy tail of the electrons accelerated at the shock front. The analysis of X-ray spectra can then provide information on the physical mechanisms that limit the energy achieved by the electrons in the acceleration process. We analysed the deep observations of the XMM-Newton SN 1006 Large Program. We performed spatially resolved spectral analysis of a set of small regions in the nonthermal limbs and we modelled the X-ray spectra by adopting models that assume different shapes of the cutoff in the electron spectra. We found that radiative losses play a fundamental role in shaping the electron spectrum in SN 1006. In fact, a loss-limited model provides the best fit to all the spectra and this indicates that the shape of the cutoff in the electron momentum (p) distribution has the form $exp[-(p/p\_cut)^2]$.

Search for correlation between giant radio pulses and hard X-ray pulses from the Crab pulsar

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We made simultaneous observations of radio (Kashima 34m and Usuda 64m dishes in Japan, 1.4GHz) and hard X-ray (Suzaku satellite, 15-75keV) pulses from the Crab pulsar for total 12.7 hours on three occasions in 2010-2011. Based on these datasets we have searched a correlation between giant radio pulses (GRPs) and X-ray pulses, and found that peak X-ray flux concurrent with main phase GRPs showed a statistically marginal increase by 21.5 +/- 8 percent (2.7 sigma significance) over the average X-ray flux when radio pulses were normal. We will discuss physical implications of this correlation, if it is proved to be real.

Suzaku Studies of the Supernova Remnant CTB109 and its Central Magnetar 1E 2259+586

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Using Suzaku, we are studying supernova remnants (SNRs) that host central magnetars; the present study focuses on the supernova remnant CTB109 and the associated magnetar 1E 2259+586. Through imaging spectroscopy with Suzaku, the peculiar half-moon morphology of this SNR was found to have arisen as its shell expansion was disturbed by a giant molecular cloud. We found the SNR to have an explosion energy of (1.7-7.0)E+51 erg/s, approximately solar abundances, and an age of 1.3-1.7 kyr. Thus, CTB109 does not show any peculiarity. However, its age is exceeded, by a factor of 20, by the characteristic age of 1E 2259+586, 230 kyr. We suggest that this apparent discrepancy can be solved if the characteristic age of 1E 2259+586 is re-estimated by properly considering decay of its magnetic field. When this correction is incorporated, other magnetically-powered pulsars, including magnetars and Central Compact Objects, may become much younger than their characteristic ages suggest. This inference is supported by very tight concentrations of these objects to the Galactic plane. It is further suggested that such neutron stars could be born with a rather high rate, and form the dominant population of new-born neutron stars.

Equilibrium Models for Magnetized Neutron Stars in General Relativity

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Neutron stars can be characterized by very strong magnetic fields. The magnetar paradigm for AXPs and SGRs, requires field in excess of 1e14G, and the recently proposed millisecond-magnetar model for GRBs advocates the possibility of even higher magnetic fields 1e16G. Strong magnetic fields are supposed to originated during mergers, and to strognly influence both the electromagnetic and gravitational wave signals. A strong magnetic field is supposed to induce deformations in a NS that in principle might give rise to gravitational wave emission in the case of rapid rotators. Modeling the role and effects of strong magnetic fields is thus necessary to properly constrain the properties of NSs. We present here numerical models of magnetized NS derived in the so called XCFC approximation, and new publicly avaialable code XNS to compute magnetized configuration for NSs. Results are shown for purely toroidal, purely poloidal configurations as well as for mixed case, usually referred as twisted torus.

Unifying neutron stars: advances, problems and initial parameters

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We discuss recent progress in grand unification models for neutron stars from the point of view of population synthesis modeling and analysis of initial parameter distributions.

At first we discuss unsolved questions about initial magnetic field distribution related to the gap in spin periods of close-by cooling isolated neutron stars. This is done in the framework of the model presented by Popov et al. (2010), which unifies radiopulsars, magnetars and M7-like sources. Then we demonstrate how CCOs can be added into the unification scheme using re-emerging magnetic fields and discuss how this is confirmed by the population of NSs in HMXBs. Finally, we analyse initial spin period distributions and demonstrate that a wide distribution presented by Noutsos et al. (2013) can be brought to correspondence with results by Popov & Turolla (2012) if magnetic field is decaying on a timescale about 5 Myrs, or if NSs with long derived initial spin periods (in the sample by Noutsos et al. 2013) had their magnetic fields significantly buried when NSs were much younger.

The Magnificent Seven see (Infra)red

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In recent years it has been suggested that the observed diversity of neutron stars can be explained by magneto-thermal evolution, where the decay of high magnetic fields provides an additional heating mechanism for the neutron star. As an alternative scenario for the unification of the different observed neutron star populations, supernova fallback disk models have been discussed. According to these models, the amount of fallback material plays an important role in determining the neutron star flavor. The fallback material forms a disk, and its torque slows down the neutron star rotation, providing also additional heating to the neutron star. In this model, magnetars are expected to have the most massive fallback disks, followed by those of the Magnificent Seven (thermally emitting neutron stars), while the rotation-powered pulsars have only a negligible amount of fallback material.

We will report on our Herschel and Spitzer Infrared observations of the Magnificent Seven to search for (residual) fallback disks around them. In particular, we will discuss two cases of enhanced infrared emission in the neutron star vicinity.

X-ray follow-up observations of confirmed and potential TeV supernova remnants

Gerd Puehlhofer[1] & HESS Collaboration
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Amongst the numerous new TeV sources that have been detected in recent years, supernova remnants (SNRs) present a rare class. Only in a handful of cases is the TeV emission unambiguously associated with the SNR shell, like in the historical SN 1006 or in the X-ray-detected SNRs RX J1713.7-3946 and RX J0852.0-4622. To unambiguously establish an association of TeV sources that were discovered in Galactic plane surveys - most notably with the HESS Cherenkov telescopes - with SNR shells remains demanding. In this presentation, follow-up observations of HESS TeV sources with XMM-Newton will be reported, where a shell association is either secured - like in the case of HESS J1731-347 - or is under debate.

Westerlund1 Transient AXP: Long-term Phase-coherent X-ray Timing & Pulse-Phase Spectroscopy of CXOU J164710.2-4552

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We present a new phase-coherent timing analysis and pulse-phase coherent spectroscopy for the whole outburst duration (~ 3 yr) of the transient X-ray anomalous pulsar CXOU J164710.2-455216 using *Chandra X-ray Observatory* and *XMM-Newton* data. The new timing solution for the pulsar spin period, period derivative and second period derivative was achieved by phase connecting 11 XMM-Newton and Chandra X-ray Observatory observations from September 2006 to August 2009, the longest baseline yet for this source, implying a spin-down surface dipolar magnetic field of $\sim 10^{14}$ G, confirming that this source is not a low-B magnetar.

We investigate the pulse profile shapes, their energy dependence and evolution. We show how different pulse components evolve differently over time, which hints at the physical processes taking place on the star. The spectral analysis is presented from the perspective of previous pulse profile analysis of the source and magneto-thermal evolution models.

Is there a magnetar wind nebula around Swift J1834.9-0846?

Andrea Tiengo
IUSS Pavia

We present an extensive analysis of the available X-ray observations of the magnetar Swift J1834.9-0846, concentrating in particular on the diffuse emission. The possible interpretation in terms of a wind nebula powered by the magnetar, in analogy to the PWN seen around rotation-powered neutron stars is very interesting. However, the spatial, spectral and timing properties of the diffuse features observed at different angular scales around this magnetar can also be well explained by X-ray dust scattering and used to derive some constraints on the source distance.

The maximum period of pulsars as a probe of fundamental physics

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No pulsars with spin periods larger than 12 seconds have been detected so far. This sharp limit of periods seems to be real and not caused by selection effect, since X-ray pulsars are not subject to physical limits to the emission mechanism nor to biases against detection of sources with longer periods. The state-of-the-art simulations of magneto-thermal evolution show that a highly resistive layer in the innermost part of the crust of neutron stars naturally limits the spin period. The existence of a maximum spin period could be the first observational constraint to the poorly known properties of matter in the inner crust of neutron stars, suggesting in particular the presence of a nuclear pasta phase, or a very inhomogeneous composition.

Solving the Vela pulsar infrared excess problem

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Our previous IR studies of the young Vela pulsar with the VLT/ISAAC and Spitzer telescopes have shown a dramatic infrared flux excess over a flat optical-UV spectrum of the pulsar. Such an excess could be caused either by a fall-back disc around the pulsar, possibly formed by supernova ejecta, or by an unresolved extended feature of the pulsar wind nebula, one of which has been detected by us in JH bands within 1.5 arcsec from the pulsar, or by a population of magnetospheric relativistic particles with a steep energy spectrum. To distinguish between these possibilities we have performed deep high spatial resolution observations of the Vela pulsar with the adaptive optics in the HK bands. We will present and discuss the results of the observations.

Chapter 4

Energetic phenomena in non-accreting neutron stars and their effects on the surroundings

Modeling statistical properties of the X-ray emission from aged Pulsar Wind Nebulae

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Recent X-ray observations have allowed to identify many HESS sources as aged Pulsar Wind Nebulae (PWNe), then triggering investigations on the late evolutionary phases of PWNe. Here I will focus on some statistical properties of these sources.

Bamba et al. (2010), measuring the X-ray sizes of old PWNe, found a steady increase in size with the nebular age, up to about 10^5 yr. They concluded that these PWNe keep expanding for a long time, contrary to the expectation that a reverse shock squeezes the PWN before the onset of the Sedov phase. In order to allow X-ray emitting electrons to reach large distances from the pulsar, they also assumed a weak nebular field and/or an efficient diffusion.

I propose that the observed trend comes instead from the combination of the evolution of objects expanding under a wide range of ambient densities. PWNe re-brighten when they are compressed by the reverse shock, and this is the last chance for them to be detectable. In this way the observed trend can be reproduced rather naturally. Also the correlation found by Mattana et al. (2009), between the X-ray PWN flux and the pulsar spin-down luminosity, could be accounted for by the same scenario.

RRAT J1819-1458 and its extended X-ray emission

Ascensión Camero Arranz & Nanda Rea
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We present new imaging and spectral analysis of the recently discovered extended X-ray emission around the high magnetic field rotating radio transient RRAT J1819-1458. We used two Chandra observations performed for this object in 2008 May 31 and 2011 May 28, respectively. The diffuse X-ray emission is detected with a significance of ∼19 sigma in the image obtained by combining the two observations. We discuss about possible scenarios for the origin of this diffuse X-ray emission.

Particle Acceleration and Magnetic Fields: Looking at the Northwestern Rim of RCW 86 with Chandra

Daniel Castro
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Non-thermal X-ray emission has been detected from several young shell-type supernova remnants (SNRs), including RX J1713.7-3946, and Vela Jr. These X-rays are believed to be synchrotron radiation from electrons accelerated to TeV energies at the shocks, interacting with the compressed, and possibly amplified, local magnetic field. Observations of gamma-ray emission from several SNRs in the TeV range confirm that particles are being accelerated to energies approaching the knee of the cosmic ray spectrum in these remnants. However, while it is broadly believed that diffusive shock acceleration (DSA) in SNRs produces the bulk of cosmic rays below 1 PeV, we still lack a detailed understanding of the acceleration process and its effects on the the system, such as magnetic field amplification (MFA) and modifications to hydrodynamic evolution. I will report on our recent observations of the NW rim of SNR RCW 86 with the Chandra X-ray Observatory. This deep look into this SNR allow us to constrain the value of the post-shock magnetic field and the properties of the shock, and hence gain insight into the nature of the cosmic ray acceleration mechanism.

Magnetic Field Instabilities in Neutron Stars

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We investigate the instability of purely poloidal magnetic fields in nonrotating neutron stars by means of three-dimensional general-relativistic magnetohydrodynamics simulations. Our aim is to draw a clear picture of the dynamics associated with a hydromagnetic instability in a neutron star and to obtain indications on possible equilibrium configurations from the final state reached by the system. Furthermore, the internal rearrangement of magnetic fields is a highly dynamical process, which has been suggested to be behind magnetar giant flares. Our simulations can provide realistic estimates on the electromagnetic emission which should accompany the flare event. In particular, we find that the emission matches the duration of the initial burst in luminosity observed in giant flares, giving support to the internal rearrangement scenario proposed by Thompson and Duncan.

The Guitar Nebula Studies at Optical Wavelengths

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The Guitar is an extended Hα nebula produced by PSR B2224+65 moving supersonically through the ISM. It is a typical example of pulsar bowshock nebulae discovered so far only around several pulsars and radio silent neutron stars. We present some results of the Guitar observations carried out with the 6-m BTA and 3.5-m TNG telescopes. The long slit spectroscopy of low and medium spectral resolution in wide and narrow spectral ranges, respectively, and Hα Fabry-Perot interferometry were done to study some aspects of bowshock physics and to clarify a relation between the bowshock, ISM, and pulsar parameters. Potentially, the spectroscopy would allow us to estimate magnitude and direction of the pulsar velocity and the pulsar distance independently.

A fast-moving radio-quiet pulsar with a very unusual X-ray trail

Andrea De Luca
INAF-IASF Milano

The Large Area Telescope onboard the Fermi mission opened a new era in pulsar astronomy by detecting gamma-ray pulsations from more than 120 rotation-powered pulsars, about 30% of which are not seen at radio wavelengths. We are performing a systematic X-ray follow-up campaign of Fermi pulsars with XMM-Newton, Chandra, Suzaku and Swift/XRT. PSR J0357+3205 is one of the most interesting objects in our harvest. Radio-quiet, with a small spin-down luminosity (and possibly close to us), such a pulsar displays a peculiar, 9 arcmin-long elongated structure of diffuse X-ray emission. Chandra multi-epoch images allowed us to measure a large proper motion for PSR J0357+3205, along a direction perfectly aligned to the main axis of the elongated nebula, pointing to a physical link between the pulsar space velocity and the mechanism producing the diffuse X-ray emission. However, a standard interpretation of the feature as a ram-pressure confined synchrotron nebula is not consistent with Chandra and XMM-Newton data.

The power of X-ray observations in identifying TeV emitting pulsar wind nebulae: The case of HESS J1818−154

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Pulsar wind nebulae (PWNe) are the most abundant class of Galactic TeV γ-ray sources detected with the High Energy Stereoscopic System (H.E.S.S.). Often, follow-up X-ray observations have provided the final piece of evidence for their identification. In some well-studied cases a softening of the X-ray and/or γ-ray spectra with increasing distance from the pulsar is observed, which is the ultimate proof of a scenario where particles are accelerated by a central source and are cooling while diffusing away. Due to the limited angular resolution of ground-based γ-ray observations, this feature might often only be detectable in X-rays.

Here, we report on results from a recently performed XMM-Newton observation towards the TeV γ-ray source HESS J1818−154 which is consistent with originating from the center of the shell-type supernova remnant G15.4+0.1. The new XMM-Newton data reveal an extended and diffuse X-ray source compatible in size and position with HESS J1818−154. The X-ray emission has a hard powerlaw-like spectrum and appears to be more compact at higher energies. We discuss the implications of these new results in the context of a PWN scenario.

"Black widow" binary systems

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The existence of millisecond pulsars with very low-mass companions in close orbits is challenging from the stellar evolution point of view. We calculate in detail the evolution of binary systems self-consistently, including mass transfer, evaporation and irradiation of the donor by X-rays feedback, demonstrating the existence of a new evolutionary path leading to short periods and compact donors as required by the observations of PSR J1719-1438 and PSR1311-3430 recently discovered in gamma rays. We show that the high mass of the neutron stars is naturally predicted, along with the rest of the observed parameters (particularly the extremely low hydrogen abundance found in the latter). A general assessment of the evolution of black widows and "redback" cousins is given.

The stability of strong waves and its implications for pulsar wind shocks

Iwona Mochol & John G. Kirk
Max-Planck-Institut fuer Kernphysik

Strong waves can mediate a shock transition between a pulsar wind and its surroundings, playing the role of an extended precursor, in which the energy is effectively transferred from fields to non-thermal particles. The damping of such precursors results in an essentially unmagnetized shock.

In this context, I will discuss the stability of strong waves and its implications for particle acceleration and the properties of shocks. Those with stable precursors can exist in winds of most isolated pulsars, but the precursors may be unstable if the external pressure is high, as in W44. Pulsar wind shocks in eccentric binary systems, such as PSR 1259-63, may go through phases with stable and unstable precursors, and a switch between these phases may be accompanied by enhanced emission from both the precursor and the termination shock.

Supernova Remnant Candidates in the ROSAT All-Sky Survey

Tobias Prinz & Werner Becker
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Identified radio supernova remnants (SNRs) in the Galaxy comprise an incomplete sample of the SNR population due to various selection effects. ROSAT performed the first All-Sky Survey (RASS) with an imaging X-ray telescope and thus provided another window for finding SNRs and compact objects that may reside within them. Meanwhile, 14 new SNRs were identified in multi-wavelength identification campaigns based on this RASS data (cf. Prinz & Becker 2013 for a summary) . The current list of RASS SNR candidates still includes 73 sources, which will be very promising to study with eROSITA. In the poster we report on the data analysis and characterize the most promising candidates.

Intrabinary Shock Emission From Black Widows and Redbacks

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Millisecond pulsars in close ($P_b < 1$day) binary systems provide a different view of pulsar winds and shocks than do isolated pulsars. Since 2009, the numbers of these systems known in the Galactic field has increased enormously. We have been systematically studying many of these newly discovered systems at multiple wavelengths. Typically, the companion is nearly Roche-lobe filling and heated by the pulsar which drives mass loss from the companion. The pulsar wind shocks with this material just above the surface of the companion. We will discuss various observational properties of this shock, including radio eclipses, orbitally modulated X-ray emission, and the potential for γ-ray emission. Redbacks, which have larger, likely non-degenerate companions, generally have more luminous shocks than black widows which have very low mass companions. This is expected since the more massive redback companions intercept a greater fraction of the pulsar wind. We will also compare these systems to accreting millisecond pulsars in quiescence, which may represent a redback or black widow like phase with the radio pulsations eclipsed throughout their orbit.

Supernova Dust and Ejecta Illuminated by Pulsar Wind Nebulae

Tea Temim
NASA Goddard Space Flight Center

The interactions between the pulsar wind nebula (PWN) and the surrounding supernova ejecta in composite supernova remnants (SNRs) serve as an important tool for determining the system's properties that may otherwise be unobservable. These properties include the SNR and PWN dynamics, elemental abundances, characteristics of newly-formed supernova (SN) dust, and properties of the SN ejecta and circumstellar material (CSM) that provide clues about the nature of the SN progenitor. The PWN provides a unique heating mechanism for the inner SN ejecta and dust that have not yet been mixed with the ambient material, making them easily separable from the surrounding interstellar medium (ISM). Identification of the ejecta and its properties provide crucial limits on the mass and dynamics of these systems that help constrain current PWN evolution models. Infrared signatures of this interaction are particularly important since high absorption along the line of sight prohibits optical and X-ray searches for SN ejecta in many composite SNRs. I will present several examples of systems that exhibit the PWN/SNR interaction, including the Crab Nebula, Kes 75, G54.1+0.3, G21.5-0.9, and MSH 15-56, and discuss what we have learned from recent infrared and X-ray observations.

TeV Pulsar wind nebulae observations & modeling: issues and lessons

Diego F. Torres[1], Jonatan Martín[1], Analia Cillis[2] & Emma de Oña Wilhelmi[1]
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We will briefly introduce the pulsar wind nebulae (PWNe) observed at TeV by the different experiments and the perspectives for a population build-up with the Cherenkov Telescope Array. Then, we will discuss theoretical models for them from the point of view of an evolutionary, fully time-dependent scenario. Issues impacting the understanding of PWNe observations driven by approximations done in the theoretical assumptions will be uncovered. Cases such as Crab and 3C58 will be compared, as examples or luminous and very dim cases of young PWNe. Finally, we will present studies aimed to clarify the conditions of self-synchrotron domination and possible equipartition biases in observed sources.

Discovery of an Infrared Bow Shock near a Pulsar

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We will report our discovery of an infrared bow shock around the middle-aged pulsar PSR J1549-4848. The bow shock was detected in our Spitzer IRAC 8.0, MIPS 24 and 70 μm imaging and Spitzer IRS 7.5–14.4 μm spectroscopic observations, and also in the WISE all-sky survey at 12 and 22 μm. Results from our detailed analysis of the multi-wavelength data of the bow shock will be given. Specifically we studied the shape of the bow shock, estimated its emission properties, and found a few emission features in the IRS spectrum. We will discuss the origin of this bow shock and suggest that it is possibly driven by PSR J1549-4848, which should then be expected to have a highly collimated pulsar wind. If this is confirmed through X-ray and/or VLBI imaging, the IR bow shock would represent a type of pulsar wind interaction with the ISM that can be expected but has been seen for the first time.

Chapter 5

Open questions and prospects for future missions and experiments

Autonomous Spacecraft Navigation With X-ray Pulsars

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An external reference system suitable for autonomous space navigation can be defined by making use of the characteristic X-ray signals emitted from pulsars. Their periodic signals have timing stabilities comparable to atomic clocks and provide characteristic temporal signatures that can be used as natural navigation beacons, quite similar to the use of GPS satellites for navigation on Earth. By comparing pulse arrival times measured on-board the spacecraft with predicted pulse arrivals at a reference location, the spacecraft position and velocity can be determined autonomously and with high accuracy everywhere in the solar system and beyond. The unique properties of pulsars make clear already today that such a navigation system will have its application in future astronautics. We will briefly describe the basic principle of pulsar-based navigation and report on the current development status of this novel technology.

eROSITA: Status and its Scientific Prospects for Neutron Stars and Supernova Remnants

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eROSITA (extended ROentgen Survey with an Imaging Telescope Array) is the core instrument on the Russian Spektrum-Roentgen-Gamma (SRG) mission which is currently scheduled for launch in fall 2014. eROSITA will perform a deep survey of the entire X-ray sky. In the soft band (0.5-2 keV), it will be about 30 times more sensitive than ROSAT, while in the hard band (2-8 keV) it will provide the first ever true imaging survey of the sky. The design driving science is the detection of large samples of galaxy clusters to redshifts z ¿ 1 in order to study the large scale structure in the Universe and test cosmological models including Dark Energy. In addition, eROSITA is expected to yield a sample of a few million AGN, including obscured objects, revolutionizing our view of the evolution of supermassive black holes. The survey will also provide new insights into a wide range of astrophysical phenomena, including neutron stars, pulsars and diffuse emission from supernova remnants.

High energy radiation and interstellar gas in the young γ-ray SNRs RX J1713.7−3946 and RX J0852.0−4622

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We present that two young VHE γ-ray SNRs, RX J1713.7−3946 (G347.3−0.5) and RX J0852.0−4622 (Vela Jr.), show good spatial correspondence between the VHE γ-rays and the interstellar gas. This result provides a support for the hadronic origin of VHE γ-rays in these SNRs. Additionally, we show a new detail comparison with the interstellar gas and the synchrotron X-rays in these SNRs. The X-ray emissions are enhanced around the interstellar gas cased by the amplification of the magnetic field as argued into detail by Inoue et al. (2012). Additionally, in RX J1713.7−3946, the spectra of synchrotron X-rays became hard around the dense molecular clumps. These distributions are strongly supported that the shock waves interact with the interstellar gas and are suggested effective cosmic-ray accelerations around the dense molecular clumps. On the basis of these results, we show a new picture of cosmic-ray acceleration in the young VHE γ-ray SNRs and conclude that the interstellar gas plays a crucial role in producing the γ- and X-rays in the SNRs.

Fast Shock Waves and Particle Acceleration in the Remnant of SN 1006

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We present early results from a long Chandra observation of the remnant of SN 1006. Deep X-ray observations allow study of the variation in shock velocity around the shell and elucidate physics of nonthermal and diffusive shock acceleration in unprecedented detail. In the northeast, where shocks are nonthermally-dominated, velocities are around 5000 km/s, but in the thermally-dominated northwest, velocities are only 3000 km/s. However, even in the northwest, we find some regions where the shock is dominated by nonthermal emission, and proper motions of these small filaments show a velocity of 5000 km/s, virtually identical to those seen in the northeast. Faster shocks in the nonthermal regions are consistent with a lower pre-shock density there, and with the theoretical view that faster shocks can enhance synchrotron X-ray emission by boosting the peak frequency emitted by relativistic electrons with an energy equal to the exponential cutoff in the power-law electron energy distribution predicted by diffusive shock acceleration theory. Thermal and non-thermal regions, with strongly contrasting X-ray spectra and proper motions, found within close proximity to one another, indicate that interstellar density inhomogeneities must exist on pc scales, even at the location of SN 1006 over 500 pc above the Galactic plane.

Name Index