HIGH-ENERGY ASTROPHYSICS

The high energy sky and multi-wavelength/messenger observations as probes of the physics of extreme compact objects

Neutron Stars, Stellar Mass Black Holes, Gravitational Wave Events & Gamma Ray Bursts

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Neutron Stars (NSs) and Stellar Mass Black holes (BHs) are the densest compact objects in the Universe. They involve a great deal of interest not only in a variety of astrophysical processes and themes, but also in fundamental physics. For instance, the equation of state (EoS) of ultradense matter in the core of NSs holds key information on the Strong Force; owing to their extreme compactness BHs and NSs provide an ideal environment to investigate gravity in the strong-field regime by studying the motion of matter and light very close to them. State of the art research on compact objects involve observations which often extend over a large range of frequencies of the electromagnetic spectrum, with X-ray and gamma-ray studies playing a prominent role; they also entail the development of advanced theory and models.

The groundbreaking discovery of gravitational wave signals from merging BH and NS binaries have opened up a new window in the study of General Relativity and marked the coming of age of multimessenger astronomy. Amongst the most extraordinary discoveries of the last decade, as evidenced also by the 2017 and 2020 Nobel Prizes in Physics, have been in the field of compact objects.

The high energy group in Rome has a long-standing record of activities in all these fields which led to a number of important discoveries: in the following some of the topics faced during the last year are briefly described.

BHs in X-ray binary systems

Black Holes are the most compact objects in the Universe. When accreting mass from a companion star, they offer us the possibility to study clean accretion physics, without the additional complexity resulting from hard surfaces or bipolar magnetic fields. Decades of studies have shown that accretion on black holes is extremely turbulent, with characteristic timescales ranging from years down to milliseconds discovered in the radiation emitted by the infalling matter. Our group has held a key leading role in studying this variable emission, proposing what is the currently favoured model for interpreting the fastest features (Stella & Vietri 1998, Ingram et al. 2009, Veledina et al. 2013), and contributing to the observational scenario with studies on single sources and classification efforts (Casella et al. 2005).

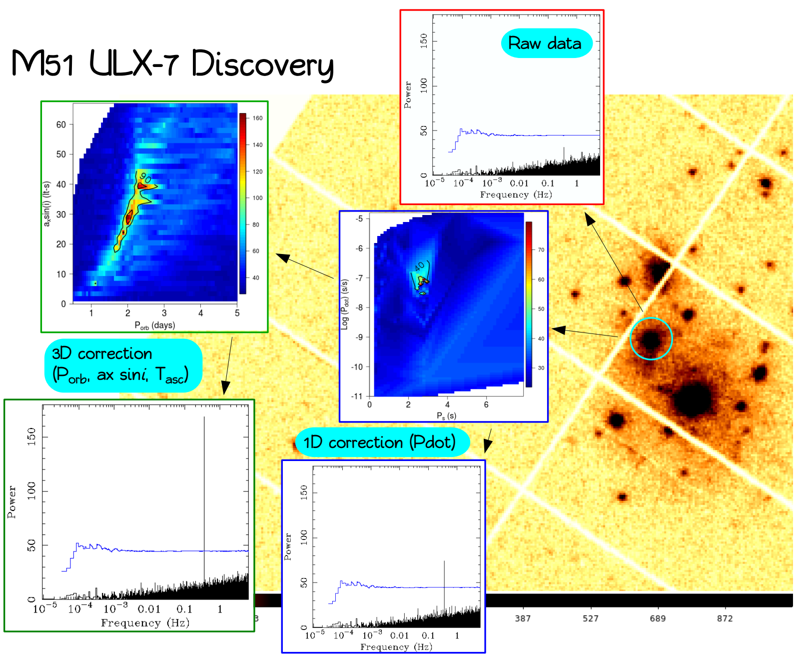

Fig. 1. Scheme of the signal search procedure adopted for the discovery of new PULXs. In many cases the signal is not detectable in the power spectrum (PSD) of raw data (red squared inset). As a first step photon event times are therefore corrected in order to take into account possible presence of period variations (both intrinsic or due to an orbital motion; blue insets); if a signal is present it is often detected at this stage. In the latest step a full orbital solution is considered providing the best possible correction (green insets).

In recent years members of our group have participated to - and in some cases led - key discoveries of similar variability patterns in the radiation emitted by matter ejected by accreting black holes (Casella et al. 2010, Gandhi et al. 2010, 2017). Our group has since been very active in studying this variable emission and its strong correlation with the emission from the inflowing matter. This includes carrying out state-of-the-art observations to characterise its properties, and participating to its physical modelling. Our recent works brought to the discovery of a nearly constant dumping timescale in the infrared emission from a jet (Vincentelli et al. 2019), to the first characterisation of rapid variability in the radio emission from a jet (Tetarenko et al. 2019, Tetarenko et al. in prep.), and to strong constraints to the misalignment between the jet and the accretion disk (Vincentelli et al. 2020).

NSs in extreme X-ray binaries

Ultraluminous X-ray sources (ULX) are off-nuclear objects detected in nearby galaxies with X-ray luminosities above 10^{39} erg s^{-1}, i.e. the Eddington luminosity (L_{Edd}) for a black hole (BH) of 10 $M_{\odot}$. Since early discoveries in the '70s the high luminosity of ULXs has been interpreted as accretion at or above the Eddington luminosity onto BHs. In the latest years fast coherent pulsations have been discovered in the X-ray light curves of six distinct ULXs with luminosities in the $10^{39} \div 10^{41}$ erg s^{-1} range, unambiguously associating these ULXs with accreting NSs, therefore a compact object with mass of $\sim 1.4 M_{\odot}$. These X-ray pulsars demonstrate that 1) up to a large fraction of ULXs might host an accreting NS, and 2) accreting NSs can attain extreme luminosities, above 500 times L_{Edd}, which is hard to interpret in the context of standard accretion models.

In this context, our group proposed a new model for the accretion onto pulsating X-ray sources (PULX) and led the discovery of three of them: the farthest and brightest of the class (NGC 5907 ULX-1; Israel et al. 2017a), the fastest (NGC7793 P13; Israel et al. 2017b) and the one in the tightest orbit (M51 ULX-7; Rodríguez Castillo et al. 2020). These discoveries were possible thanks to *ad hoc* pipelines and software for timing analysis first developed within the EXTraS project[1]. These take into account many different parameters such as the possible presence of a first period derivative and of an orbital motion (see Fig. 1). Two XMM Programs were approved in order to look for new PULXs and to understand the physics behind their extreme properties leading to important serendipitous discoveries (Bachetti et al. 2020, Belfiore et al. 2020, Motta et al. 2020, Pintore et al. 2020).

Relativistic Fe-lines and radiation drag

An extremely broad Fe-lines around 6 keV (hereafter Relativistic Fe Line, RFL), observed in accreting stellar mass BHs and NSs, as well as in tens of supermassive BHs in the nuclei of active galaxies, display a complex profile determined by relativistic effects of matter orbiting in accretion disks down to the innermost stable circular orbit where speed as high as ~ 0.5 c are attained (see Fig. 2 and Fabian et al. 1989).

[1] http://www.extras-fp7.eu/

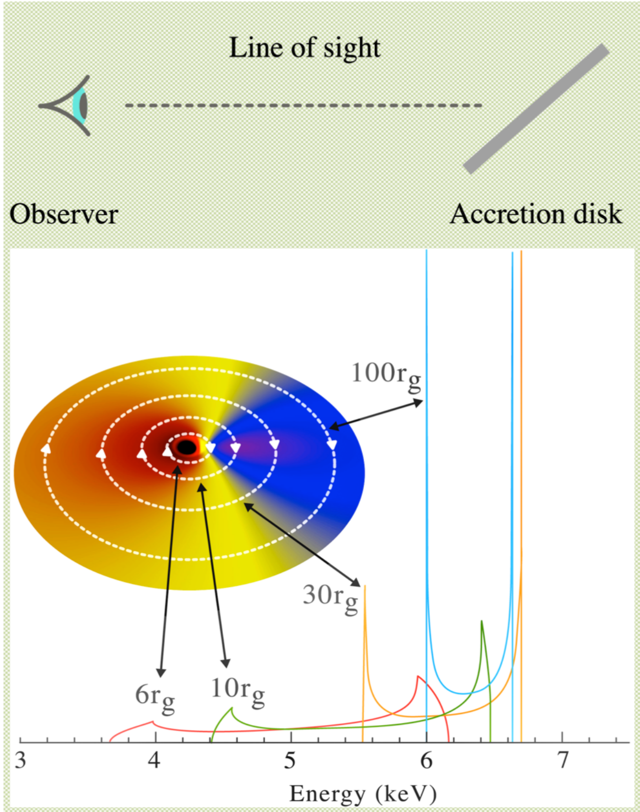

Fig. 2. Relativistic Doppler shifts, gravitational redshift, photon bending and beaming affect the spectral shape and flux observed from each point of the accretion disk, leading to a characteristic, extremely broad Fe-line profile. The contribution of different radii to the profile is shown ($r_g = GM/c^2 \simeq 1.5(M/M_{\odot}$ km) (La Placa et al. 2020).

Besides disk properties, RFLs encode key information on the motion of matter in the strong field regime of General Relativity, besides the disk properties. Observations have already yielded measurements of BH spin close to the maximum allowed by the Kerr spacetime. Since the pioneering works in the 90's, the exploitation of RFLs has evolved into major research areas in high energy astrophysics. We developed a new method based on RFLs to measure with high precision the radius-to-mass ratio (R/M) of weakly magnetic, disk-accreting neutron stars by exploiting the occultation of parts of the inner disk by the star's body. This in application to data from very large area X-ray instruments (Ray et al. 2019) can provide much need information on the equation of state of matter at supranuclear density and the repulsive regime of the strong force (see Fig. 3 and La Placa et al. 2020). We developed also an alternative, variability-based method to constrain the NS structure (Maselli et al. 2020).

The radiation produced by accretion is in part intercepted by the inflowing matter. Besides exerting a radial force, as familiar from the Eddington argument, this radiation affects the momentum of matter, altering its motion. The latter is the so-called Poynting-Robertson effect (or radiation drag). In recent years, our Team derived the first fully general relativistic treatment of the Poynting-Robertson effect in the highly curved space-time of compact objects (Bini et al. 2009, 2011) and

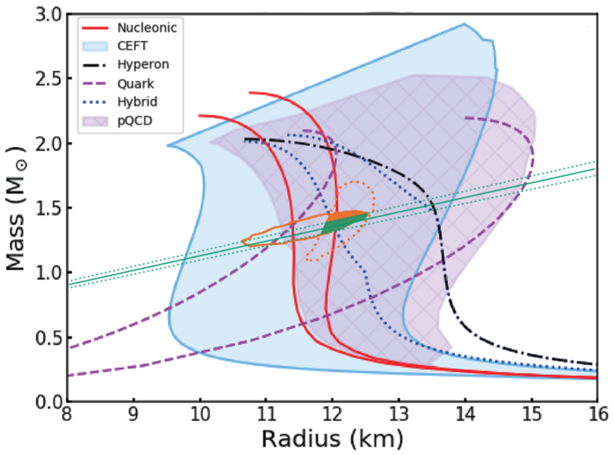

Fig. 3. Limits on the mass–radius plane obtained with RFL method (green lines); open curves and areas represent equations of state for different underlying microphysics. The orange solid and dotted curves shows the constraint that can be obtained with two other methods. The simultaneous use of the three methods with data from very large area X-ray instruments can measure to a few percent precision the NS mass and radius (filled region in green) (La Placa et al. 2020).

studied the characteristics of the resulting non-geodetic motion under a variety of physical conditions (Bakala et al. 2019, De Falco et al. 2019, see Fig. 4).

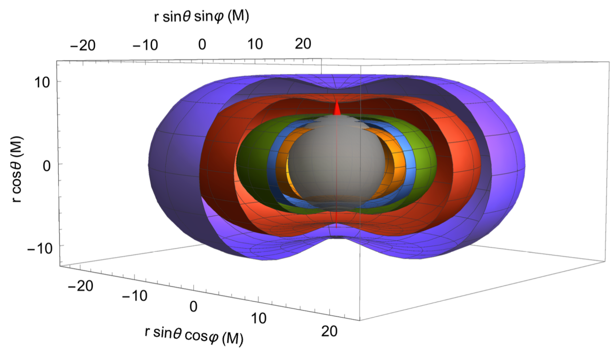

Fig. 4. Critical hypersurfaces where orbiting matter settles in rotational motion under the combined effect of radiation and gravity (including frame dragging), around a NS rotating at a frequency of 600 Hz (or a Kerr parameter of $a = 0.41$). The hypersurfaces are shown for different values of the NS luminosity (0.75, 0.78, 0.8, 0.85, 0.88 in Eddington units) (De Falco et al. 2019).

Accretion vs rotation power: the case of transitional millisecond pulsars

Millisecond pulsars (MSPs) are the quickest spinning self-gravitating objects known. These neutron stars are spun up by a previous secular phase of accretion of mass in a low-mass X-ray binary. When the mass transfer ceases, the pulsar switches on as a rotation-powered radio emitter.

In 2013, the discovery of the prototypical transitional MSP – a source that switched back and forth X-ray and radio pulsar states over a few days – finally demonstrated the link between rotation- and accretion-powered MSPs (Papitto et al. 2013). These sources are ideal probes of the complex interaction between the strong NS magnetic field and the disk plasma. Our group is heavily involved in the efforts to increase the number of known transitional MSPs (currently three confirmed sources and four strong candidates; see, e.g., Coti Zelati et al. 2019) and to characterize the emission mechanisms at work (see Papitto & De Martino 2020 for a review).

In this context, the fast optical photometer SiFAP2, currently mounted at the Telescopio Nazionale Galileo and managed by members of our group, gained a prominent role. This instrument let us discover the first optical MSP in one of such transitional systems (Ambrosino et al. 2017).

Simultaneous X-ray/optical observations proved that a single mechanism powers the pulsations observed in both bands, suggesting that rotation and accretion power might coexist in transitional MSPs (Papitto et al. 2019, see Fig. 5).

The subsequent quest for optical MSPs that we have undertaken soon after has brought to the discovery of an optical/UV signal from an accreting MSP (Ambrosino et al. 2020, submitted to Nature Astr.). This suggests that optical pulsars might be more common than expected, opening a wide discovery space for fast optical photometry with SiFAP2.

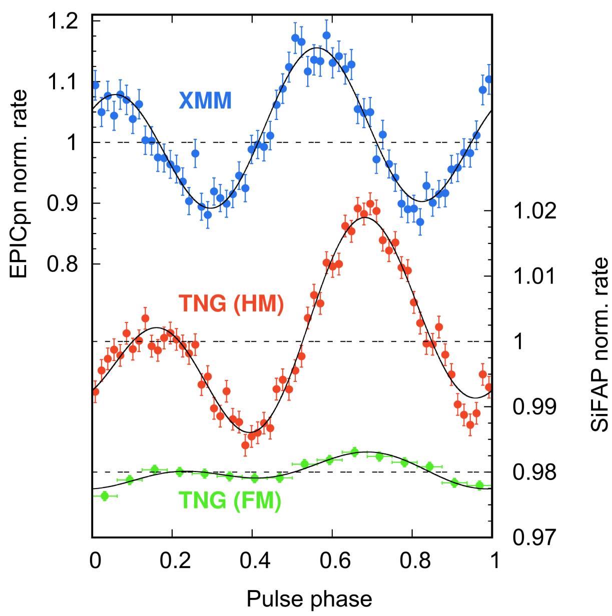

Fig. 5. Pulse profiles observed simultaneously by the ESA X-ray observatory XMM-Newton (blue points) and by the optical photometer SiFAP2 at the Telescopio Nazionale Galileo (red and green points) during the high mode of the transitonal MSP PSR J1023+0038. Green points mark the optical pulse profile observed during flares of the same source. The pulse profiles observed in different bands are almost in phase. We proposed they might be produced by synchrotron emission from relativistic electrons accelerated at the shock yielded by the interaction between the pulsar wind and the accretion disk.

Magnetars

The term 'magnetar' was coined almost three decades ago to identify isolated NSs ultimately powered by dissipation of their own magnetic energy, which usually implies that they are endowed with huge magnetic fields, up to $\sim 10^{15}$G. A large fraction of the $\sim$30 magnetars known to date have been discovered over the past two decades, through their distinctive high-energy phenomenology: bursts of X-ray/gamma-ray emission and/or enhancements of their persistent X-ray luminosity, dubbed 'outbursts'. Recently, evidence has mounted that these bursts are tightly connected with (at least a sub-population of) fast radio bursts (FRBs), bright millisecond-long radio flashes whose nature has remained elusive since the first detection reported in 2007. Our group is involved in the study of these objects since the very beginning in the '90s. Recently, among other results, we detected (in the 2009 datasets of a transient magnetar) an X-ray burst followed within 1s by a strong radio burst, further suggesting that magnetar bursts in the Galaxy may bridge the gap between ordinary pulsar radio bursts and the extragalactic FRB phenomenon (see Fig. 6 and Israel et al. 2020, ApJ, in press).

During 2020 two new magnetars have been discovered and studied by our group (Esposito et al. 2020; Coti Zelati et al. 2020b), while three new outbursts from known objects of the class have been detected (Borghese et al. 2020, Rea et al. 2020, Coti Zelati et al. 2020a).

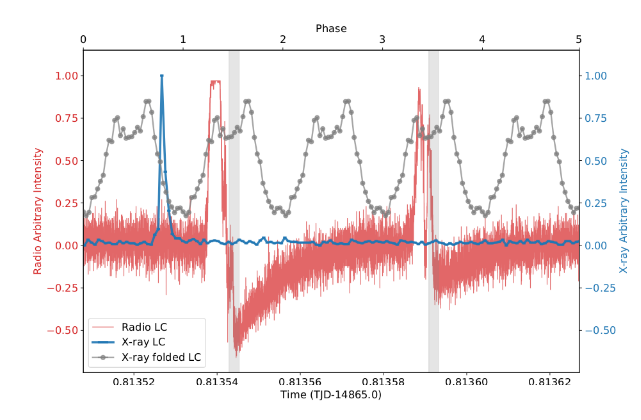

Fig. 6. X-ray and radio simultaneous observations of 1E 1547.0–5408, performed on 2009 February 3, around the time of the brightest X-ray burst and the two radio pulses. The blue line is the burst lightcurve, while the grey line is the X-ray folded light curve using the XMM dataset. The Parkes simultaneous radio light curve is shown in red. The grey shaded areas are the phase intervals of the expected peak of the radio pulse profiles extrapolated from the 2009 January 25 Parkes observation. Note that the flat top of the first radio peak, and the drop of the intensity of the radio signal below the average noise level following both pulses, are artifacts caused by the saturation of the backend.

Electromagnetic counterparts of gravitational wave events

The first detection of a binary neutron star merger through gravitational waves and photons, on the 17th of August 2017 (Ligo scientific collaboration 2017), marked the dawn of multi-messenger astronomy with gravitational waves.

It sparked the most extensive observational campaign in human history which enabled a spectacular detection of electromagnetic emission in essentially all electromagnetic bands (see Fig. 7). This multi-messenger detection revolutionised our understanding of binary neutron star merger, unveiling the origin and the physics governing short gamma-ray bursts and the existence of optical sources powered by the radioactive decay of heavy elements, known as kilonovae.

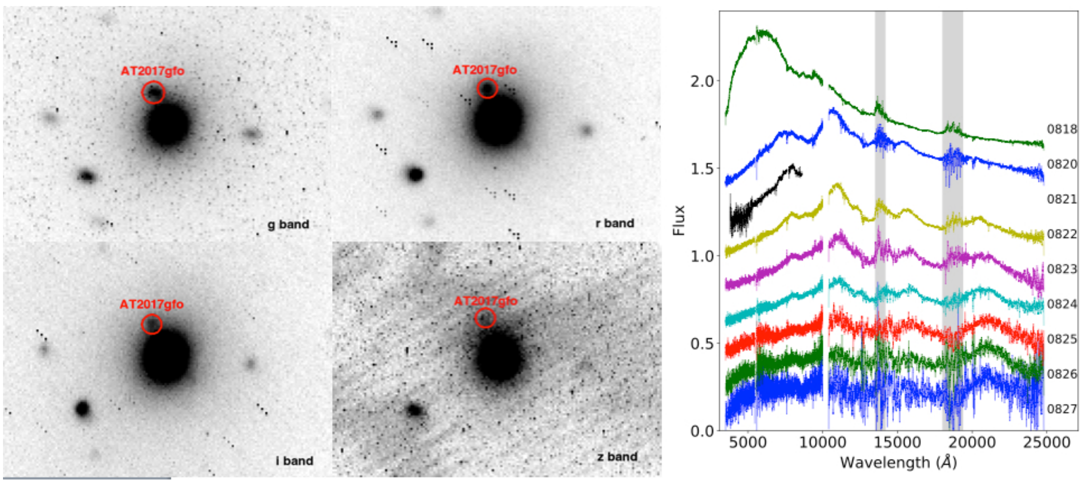

Fig. 7. Left panel - REM images in g,r,i,z band of the optical/NIR counterpart of GW 170817 (the AT2017gfo transient) inside the host galaxy NGC4993 (D = 40 Mpc), taken at T+12.8h (Melandri et al. 2017, GCN 21532 and GCN 21596); Right panel - Time evolution of the AT2017gfo spectra. The analysis and modelling of the spectral characteristics of AT2017gfo, together with their evolution with time, result in a good match with the expectations for kilonovae (KN), providing the first compelling observational evidence for the existence of such elusive transient sources. VLT X-shooter and FORS2 spectra are shown, the flux normalization is arbitrary (adapted from Pian et al. 2017)

The detection of electromagnetic signatures from the gamma-rays, to the optical and radio bands enhanced our knowledge of relativistic jets, the nucleosynthesis of heavy elements in the Universe, and the nuclear physics of neutron stars.

GW170817/GRB170817 also furnished constrains, independent from those already existent, to the unknown equation of state of NS (Ligo scientific collaboration and Virgo collaboration 2020) and the Hubble constant (Fishbach et al. 2019), extending the range of influence of multimessenger astronomy to the fields of quantum chromodynamics and cosmology. It is evident thus that the scientific potential of multimessenger astronomy is huge and covers many branches of physics. This event clearly showed the power of detecting the electromagnetic counterpart of a gravitational wave signal.

In this contest our group (involved in the GRAvitational Wave Inaf TeAm, GRAWITA, collaboration whose PI is Enzo Brocato from our observatory) participated in many of these studies (Pian et al. 2017, Tanvir et al. 2017, Brocato et al. 2018, Ascenzi et al. 2019, Ackley et al. 2020, Rossi et al. 2020) as we are involved in several international and european collaborations aiming to carry out follow-up observational campaigns in the radio, optical, NIR, X-ray, and gamma-ray bands of the gravitational wave (GW) detector triggers released by the ground-based interferometers network actually composed of the two Advanced LIGO (USA) and Advanced Virgo (Italy). Ground-based facilities used by our group include VLT Survey Telescope, Large Binocular Telescope, Telescopio Nazionale Galileo, Rapid Eye Mount Telescope, Asiago Observatory, Campo Imperatore Observatory, SRT.

In the near future, we expect great possibilities to explore more with this new field thanks to the recently developed GW detectors and their next generation operating in synergy with innovative multi-wavelenght observatories, such as the Cherenkov Telescope Array (CTA) (Actis 2011, Acharya et al. 2013), the proposed THESEUS mission (Amati et al. 2018, Stratta et al. 2018), the VEra Rubin Observatory (Ivezic 2019), the European Extremely Large Telescope (E-ELT) (Gilmozzi & Spyromilio 2009) the Square Kilometre Array (SKA) (Carilli & Rawlings 2004), and more. This will boost considerably our understanding of the high-energy Universe.

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