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Polarimetry of X-rays and messengers of High Energy phenomena

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Summary. — Astrophysics of High Energies has been historically based on radio, X-ray and γ-ray data. Understanding the mechanism and the site of acceleration of Cosmic Rays, has been probably the most important goal of this discipline. Recently high energy neutrinos and gravitational waves have shown up as new messengers and we expect a major role from X-ray observations, to understand the nature and location of the emitters. In fact X-rays have been for more than half a century the driver to study the Violent Universe. Yet one feature of this messengers, the Polarimetry, is still totally unexploited. Within a few years, a mission will add two important parameters to understand the physical context of high energy phenomena, namely the amount and angle of X-ray polarimetry.

1. – New and old messengers

Our knowledge of the Universe is based on the information we receive from messengers of different nature. Since the birth of modern science, visible radiation, whose detection was progressively powered by the development of optical technologies, in terms of imaging, spectroscopy, variability and polarimetry, has been the only valuable messenger. Around one century ago the discovery of Cosmic Rays introduced a new class of messengers, namely that of particles. Given the charged nature of the two known stable particles it was clear that, beside the extraterrestrial origin of them, their direction would be heavily affected by the magnetic fields, and they would never compete with photons to identify and angularly resolve the sources. Yet the presence of Cosmic Rays set constraints to any future picture of the Universe. Therefore the two communities of Astrophysicists and Cosmic Physicist proceeded for most of the 20th century on two independent paths. After the 2nd World War the birth of Radio Astronomy represented the first large scale extension of the e.m. band. One of the first finding was the presence of bright sources associated to past explosive events. In 1967 the pulsars were discovered. The following step forward was the opening of the windows of extrasolar X-rays and γ-rays. In particular, the unexpected detection of an outstanding phenomenology in X-rays unveiled an universe populated of compact objects. The X-ray observations have

been since the backbone of all the High Energy Astrophysics. To understand, in terms of astrophysical objects, the site and the mechanism of acceleration of Cosmic Rays has been the major driver of this science.

The detection of High Energy neutrinos and gravitational waves is, no question, a dramatic step forward in our knowledge of the so called Violent Universe. Both messengers travel straight, or almost straight, given the very low mass of neutrinos. Yet the paucity and some unexpected features of these events stress the need for a multi-messenger approach to understand where and when these events occur. In other terms we want to understand better which are the sources of these events, how frequent they are, how they evolve and in which circumstances they arrive to show up in such a dramatic way.

In the quest for sources, photons are the natural messengers. The optical and radio bands provide the richest phenomenology and the best angular resolution, but their sky is the most crowded and the less selective. On the other side X-rays and Gamma-rays are emitted in contexts much closer to those that can be figured for the GW events. Moreover X-ray missions with wide field of view do exist and Gamma-ray missions are usually intrinsically sensitive in a wide field, and both are a logic tool to search for counterparts of events showing up from unpredictable directions. Therefore we can reasonably state that these two bands are the best support to complement the observations in these new windows. Last but not least X-ray instrumentation can arrive to angular resolutions down to arcseconds or even better.

Notwithstanding the impressive sensitivity and resolutions achieved by X-ray telescopes, we can still figure an expansion of the capability to fully exploit the information associated with X-ray photons in terms of instrumental design. The start of X-ray polarimetry with high sensitivity and imaging capability is likely the most significant improvement to be achieved in a relatively short time frame.

2. – The status of X-ray polarimetry

Since the very early years of X-ray Astronomy the discovery of X-ray emission from the Crab Nebula, proofed the presence of non-thermal phenomena, in particular of synchrotron, and suggested that Polarimetry could play a major role in the diagnostics of the physical situations in the source. The team of Columbia University lead by Robert Novick performed several experiments trying to find experimental evidence of a high degree of polarization. The experiments were mainly based on two processes:

- Bragg Diffraction at 45°,
- Compton Scattering around 90°.

In both configurations the direction before and after the interaction was constrained with collimators and proportional counters were the detectors. The Bragg polarimeter had a good response to polarization, almost unaffected by systematics, but on a very narrow band. Compton polarimeters were effective only at higher energies ($> 6\,\mathrm{keV}$) where less photons are available. The use of proportional counters forced the use of square geometries that resulted in a large anisotropy in the angular response and, thence, on high systematic effects. On the other side an instrument based on collimators and proportional counters was simply equivalent to what was done in other branches of X-ray astronomy, namely spectroscopy and timing. Also the measurement, by intrinsic reasons

for the Bragg, and to compensate systematics, for the Compton, would require a rotation of the whole instrument around the view axis.

I remind the essential definitions of X-ray polarimetry. Any X-ray polarimeter is based on the dependence of a cross section on the angle between the plane of polarization of the radiation and the output channel of the instrument. In practice the outcome of an experiment of polarimetry is a modulation curve, namely an histogram of counts collected within angular bins. The histogram is fitted with a constant plus a $\cos^2$ law.

The ratio of the modulated part and the constant one is the so called *modulation*. The modulation for a 100% polarized radiation is named the *modulation factor* μ.

The sensitivity to the linear polarization is defined, as usual, on the capability to reject with a pre-defined level of confidence, the hypothesis of null signal. Given the Poisson Statistics we define as Minimum Detectable Polarization (MDP) at 99%.

$$\mathrm{MDP} = \frac{4.29}{\mu R_s}\sqrt{\frac{R_s + R_b}{T}}. \tag{1}$$

Here μ is the modulation factor, R_s the counting rate of signal (the source), R_b the counting rate of the background, T is the observing time. The statistics of these measurement is completely described in [1].

The modulated part of the curve, is to be compared not only with the fluctuations of background but also with those of the not-polarized part of the source, which is usually expected to be very large. A simple effect of this is that to detect polarization we need many more photons than to make a spectrum or simply, to detect a source. The experiments of polarimetry of this pioneering age where less sensitive than the contemporary experiments of spectroscopy or timing, but where still somehow matched, given the relevance of the polarization information. Another important point is that the rotation needed to perform the measurement of polarization was also the baseline to detect sources with the scanning collimator approach used, *e.g.* for UHURU.

The situation evolved dramatically when Einstein mission applied for the first time the technique of grazing incidence optics with imaging detectors in the focus. The imaging was drastically improved. But the major improvement was the increase of sensitivity for weak sources. The focus of X-ray Astrophysics moved toward the extragalactic sky, that was totally out of reach for the conventional polarimeters. Moreover, the rotation of the instrument, usually achieved with spinning satellites, was no more needed in the new concept of mission. Actually polarimetry was an unneeded complication and source of constraints for the main instrument.

In practice with the conventional techniques and the conventional detector, polarimetry was totally mismatched with the other subtopics of X-ray Astrophysics and, as a consequence, polarimeters were no more included in the major missions.

3. – A new detector and a new era

The situation of X-ray polarimetry had a turning point a the beginning of the 21st century, when a new detector was built that implemented a long time thought approach: the photoelectric absorption. Differently from the other two interactions, the output is an electron and not a photon. This means that the emerging particle starts to ionize soon

after its creation. In principle the ionization track produced by the photoelectron carries all the needed information, namely the point of interaction, the total energy (proportional to the total charge), the starting direction of the photoelectron. The latter is the basis of a measurement of linear polarization. A detector based on photoelectric effect could in principle serve all the subtopics of X-ray Astronomy. This was conceived in the very beginning of X-ray Astronomy but was not feasible because of a technical limitation. The interaction length of the X-ray photons is longer, by 2-3 orders of magnitude than the range of the photoelectron originated by a photon of the same energy. The information on polarization in the track of the photoelectron is contained in the direction of emission of the photoelectron. Such a direction is quickly modified by the scattering on the nuclei of the gas and is lost in the final part of the track where the direction is totally randomized but where most of the energy is transferred to the gas in the form of ionization. Therefore in order to measure this direction we must first derive the interaction point, and then fit the direction of the track in the proximity of this interaction point. The spatial scale of this analysis is much lower than the dimensions of the detector. The first requirement for a polarimeter, with an acceptable efficiency, is the extremely fine subdivision. This rules out the solid state devices but also the traditional gas counters. Also the implementation of such a technique, beside maybe the case of solar flares, could only be conceived for focal plane devices. But this was exactly the aim of this development. The goal was finally achieved by the INFN team of Pisa headed by Ronaldo Bellazzini.

The first successful attempt to build such a fine resolution device was performed on 2001 [2]. A gas cell, filled with a Ne based mixture was aimed to convert the photons. The electrons of the track would be drifted by an electric field parallel to the axis of view to a Gas Electron Multiplier. The new part was a plane of metal pads to collect the charges from the back of the GEM after the multiplication. It was based on a multi-layer technology with signals routed on an electronics in the plane. This prototype detector was limited in number (< 1000) and size ($> 200\,\mu$m) of the pixels but showed, for the first time, that a photoelectric polarimeter, sensitive in the band where X-ray Optics are effective, was feasible.

Soon after the device was evolved by implementing the same concept with a different technology. The functions of anode pad, bottom of the detector and front end electronics where all implemented in a single ASIC VLSI chip [3]. By this solution it was possible to arrive to 2000 pixels of $100\,\mu$m pitch. By two more steps a chip of 105600 pixels and a pitch of $50\,\mu$m was built [4]. Also the capability to self-trigger was implemented. The whole was vey light and very clean and able to fetch only a subset (Region of Interest) of data around the triggering pixels. This was absolutely needed in order to avoid that the dead time could diverge, with the increase of the number of pixels. Also a filling gas based on dimethylether resulted more effective than the neon based one.

With these improvements the Gas Pixel Detector was ready for space application. Also the compatibility with space environment was demonstrated through testing, that included the capability to resist to the presence of high atomic number ions. The GPD in the focus of an X-ray optics can make feasible the X-ray polarimetry. Several proposals with different combinations of telescopes and detectors have been submitted, in the last 10 years, to ASI, NASA, ESA in response to Announcements of Opportunity or considered for inclusion in larger X-ray missions by the Chinese National Space Agency.

While I am writing these proceedings, ESA is completing the phase A study of the X-Ray Imaging Polarimetry Explorer (XIPE) [5] and NASA has approved as a Small Explorer the Imaging X-Ray Polarimetry Explorer for a flight on 2020. Both missions are based on the GPD detectors.

4. – Which science with this new messenger

The implementation of the GPD resulted also in a burst of theoretical activities, that, after the pioneering age, had been almost abandoned, for starvation of data. This activity was further accelerated by the studies of XIPE and IXPE missions, that allowed to set all the matter on solid bases of feasible observations. Nowadays we can say that for almost all the classes of X-ray sources, observations have been proposed where polarimetry can help to improve our understanding of the physical situation or even clearly remove the degeneracy with respect to models present in analysis based on spectra and variability only. The most complete reviews of this literature are included in papers describing previous proposals of mission such as [6]. Also the sources, like galaxy clusters, for which a negligible degree of intrinsic polarization is expected, can be used as probes of effects of fundamental physics during the transfer of the radiation to the observer. I give a few examples of proposed observations relevant to the scenarios associated with the phenomenology of the new messengers. The two major classes are the acceleration of particles to very high energies and the Strong Gravity effects in binary systems including collapsed objects.

Many sources are candidate to explain the origin of neutrinos but, for various reasons, blazars are strong candidates. For these classes the polarimetry can play a major role. In the case of blazars, polarization signature is expected to distinguish between hadronic and leptonic jets. Within leptonic models the polarization of the comptonization bump, compared with that of the synchrotron part of the spectrum, can help to distinguish between Self-Synchro-Compton and External Compton and, in this last case, to identify the source of seed photons (disk, Broad Line Regions, etc.). The other new messenger are gravitational waves. The first LIGO detections, by the temporal structure of the event, are ascribed to the merging of two black holes. In this frame no significant energy is expected in the form of electromagnetic radiation. With the increased sensitivity expected for LIGO and VIRGO, events of different origin should be detectable. For most of these an electromagnetic counterpart could be detectable and, as usual, X-rays and gamma-rays are the best candidate ranges for this counterpart. No prediction has been so far published about polarization, but it is evident that all the ingredients, typically resulting in a high degree of polarization, such as geometrical asymmetry and strong fields, are present in these scenarios. For sure X-ray astronomy will be boosted by polarimetry to increase the understanding and the statistics of the progenitors of these gravitational wave events, namely the binary systems with at least one collapsed object.

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