Prologue: γ-Rays from Star-Forming Regions, a Historical Perspective

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Abstract At last, we are in a position to scrutinize the acceleration, diffusion and propagation processes of cosmic rays in the vicinity of supernova shocks, the interaction of both high-energy (GeV-TeV) and low-energy (100 MeV and below) cosmic rays with molecular clouds, generating high-energy gamma-rays and ionization processes respectively. This prologue provides a historical introduction to the studies of the interaction of cosmic-rays and star-forming regions.

Contrary to what people might think today, γ-ray astronomy already has a long history – "long" meaning here over 50 years. Indeed, in a pioneering paper, P. Morrison [15] established the theoretical basis of γ-ray astronomy as we know it today. In particular, he pointed out π^0 decay as a potentially important mechanism of interaction between high-energy particles ("cosmic rays") and matter in space. Other studies along the same lines followed (e.g., [2, 7, 19]), but somewhat later, as experiments began to investigate the sky at γ-ray energies.

At that time, the detection of very high-energy (VHE) cosmic rays by the air shower technique, pioneered by L. Leprince-Ringuet, was well known, but the experimental set-ups could detect only nuclei. Apart from the fact that lower energy cosmic rays had to be studied from balloons to overcome atmospheric attenuation (think of Victor Hess and his electrometer in 1912!), a long-term goal was *to find the location of "cosmic-ray sources"*, using the fact that VHE cosmic rays are almost insensitive to deviations by the weak galactic magnetic fields.

It took more progress on the theory of the development of air showers to establish criteria to detect γ-rays and distinguish them from nuclei ([12], et sq.). As a result, based on the experience gained with cosmic-rays, Čerenkov telescopes (this time in the real sense of detecting photons coming from a given direction in the sky) were

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built in the early 1960s by several groups, including on Mt Whipple in Arizona (T. Weekes et al.), and near Simferopol in Crimea (A.A. Stepanian et al.).

The first goal was of course to try and find “point sources” of γ-rays in the sky. At this time, quasars (“quasi-stellar objects”) has just been discovered ([17]: 3C273), with their unusual optical spectra and high redshifts, so the high-galactic latitude part of the sky became the prime target, even though of course the whole sky (i.e., visible from a given observatory), including parts of the galactic plane, was scanned.

However, this first era of observational γ-ray astronomy brought only upper limits, and since there were no a priori quantitative expectation that quasars should be γ-ray emitters, the field looked like a dead end to many astronomers.

The breakthrough came with the discovery of pulsars (1967, published in 1968: [11]). With their pulsating radio emission and power-law spectra, they were an entirely new class of astronomical objects. Extrapolating to high energies resulted in a “prediction” of γ-ray emission up to the TeV range ([9], et sq.), and boosted the morale of γ-ray astronomers! The fact that the emission was periodic allowed to enhance the S/N ratio, and therefore the probability of detection, by selecting events in phase with the radio emission. And the discovery of the pulsed γ-ray emission of the Crab pulsar NP0532 was indeed soon to follow [10], and could be considered as marking the real birth of γ-ray astronomy.

Since celestial sources were found to exist at TeV energies, it was of course tempting to detect them at lower energies – but from GeV energies down to the UV domain photons are absorbed by the Earth’s atmosphere without giving rise to detectable secondary particles as TeV photons do. So the techniques to be used had to be entirely different from ground-based Čerenkov telescopes. While coming also from accelerator physics, like proportional counters for X-rays or spark chambers for GeV γ-rays, these techniques had, in addition, to be adapted to be able to fly on balloons, rockets, or even better, go to space aboard satellites.

Keeping in mind the milestone date of 1967 for the discovery of pulsars, the reactivity of the community was astounding. In the framework of NASA’s “Small Astronomical Satellites”, part of the Explorer program, the first X-ray satellite, SAS-1 (aka Explorer 42, which became famous under the name of “Uhuru”) was launched in December 1970 – to last until 1973 – and the first γ-ray “observatory”, operating in the 10 MeV–1 GeV range, SAS-2 (aka Explorer 48), was launched in 1972 – unfortunately forced to silence because of an electrical breakdown after only 6 months of operation.[1]

However short-lived, SAS-2 was able to provide the first γ-ray map of part of the sky, revealing two of the most luminous pulsars and their γ-ray pulsations, the Crab and Vela, and, most importantly for our purpose in the present chapter, *diffuse γ-ray emission from the galactic plane* (see Fig. 1, [6]). After this unfortunate failure, the

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[1] Strictly speaking, the first celestial γ-rays were detected in the >70 MeV range by the OSO-3 satellite, which was a solar observatory. The main result was the detection of an excess in the galactic center direction [4].

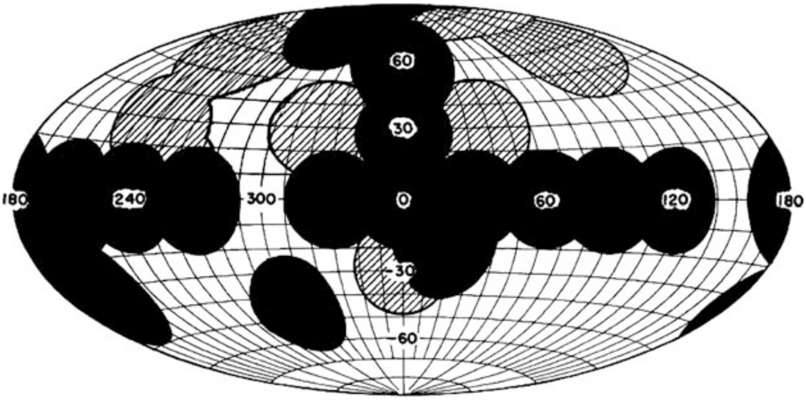

Fig. 1 The areas observed by the SAS-2 satellite in its 8-month lifetime. The Crab and Vela pulsars were detected, as well as evidence for galactic diffuse emission. Only upper limits could be obtained in the other regions (Fichtel et al. [6])

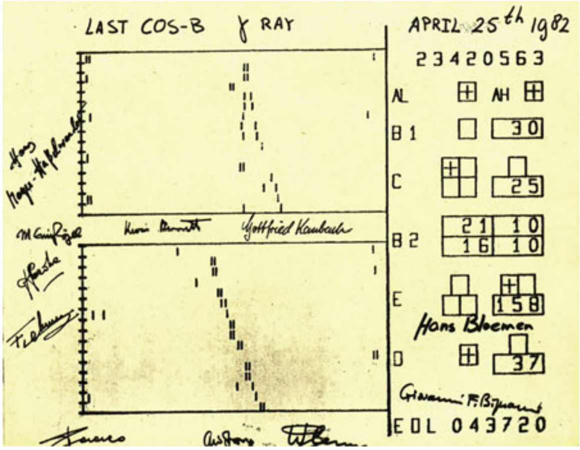

Fig. 2 The last γ-ray observed by COS-B's spark chamber. The inverted "V" is a signature of the creation of a secondary electron-positron pair as the incoming γ-ray is absorbed by the spark chamber plates. The two views are orthogonal, and allow to reconstruct the photon arrival direction with a typical resolution of ∼1° HWHM above 300 MeV. The image is signed by the main actors of the COS-B saga (Source: ESA)

leadership of γ-ray astronomy shifted across the Atlantic with the launch by ESA of the COS-B satellite in 1975. COS-B, which lasted until 1982 (see the "last photon" signature in Fig. 2), made the γ-ray all-sky a reality, with its point sources, both galactic and extragalactic, and the first detailed mapping of the galactic plane.

In other words, γ-ray astronomy really came of age in the COS-B era. Interestingly, major ingredients in our understanding of galactic γ-ray emission features fell into place during this era, almost simultaneously but independently: (i) the detection of the CO molecule, as a tracer of molecular hydrogen, at mm wavelengths, in other words the discovery of molecular clouds ([18], et sq.); (ii) the positioning of HII regions as tracers of the spiral structure of the galaxy [8]; (iii) the realization of the so-called "sequential star formation" in molecular clouds [5]; (iv) a breakthrough in the theory of cosmic-ray acceleration by shock waves [1], now known and developed as the "diffusive shock acceleration" theory. Very exciting times indeed!

This converging set of ingredients led to two major consequences on the interpretation of the galactic γ-ray emission, as seen by COS-B:

(i) The excellent correlation on the sky, both in longitude and in latitude (within $\pm 5^\circ$), with the CO distribution, immediately suggested that the π^o-decay mechanism was dominant (albeit mixed with other processes like inverse Compton in some places), and that the galactic cosmic-ray flux ("GCR": above $\sim$1 GeV, i.e., essentially insensitive to the solar modulation) had to be fairly uniform across the galaxy (e.g., [16]). Furthermore, by using distances derived from the galactic velocity curve for CO and HII regions, and masses for molecular clouds derived from a nominal CO/H_2 ratio, it was possible to feed into the γ-ray data a model for the galactic spiral arms, and then deduce the arm-interarm GCR contrast, which turned out to be not more than a factor 2–3. In turn, this supported the idea that cosmic ray nuclei diffuse very efficiently from their sources out in the galactic disk. Good news for understanding cosmic-ray propagation – but bad news to find GCR sources!

(ii) However, even the γ-ray longitude profile displayed localized "hot spots" that could not be explained by a simple CO-γ-ray correlation. Within the COS-B angular resolution ($\sim 1^\circ$ HWHM), these hot spots could be called "sources". Some of them were identified with pulsars, confirming the SAS-2 results, like the Vela pulsar.[2] Several others were unidentified, but it became quickly clear that several of them were in fact well correlated spatially with giant HII regions, excited by stellar "OB associations", or, in modern parlance, massive star forming regions. But an additional, essential feature characterized most (not all) of them: *they were also harboring supernova remnants*. For that reason, these γ-ray sources were dubbed "SNOBs" by Montmerle ([13]; see also [3]). These sources accounted for about half (5/11) of the unidentified COS-B sources, and conversely up to 3/4 of the $\sim$30 SNOB list had hints of γ-ray emission. Given the poor COS-B angular resolution, these identifications were only tentative -albeit convincing-; in particular, there was always the possibility that an unseen pulsar could be the real γ-ray source.

Still, given the context at the time, it was easy to elaborate a semi-quantitative SNOB scenario, in three parts. First, the shock wave would sweep the solar-mass members of the OB association, which would, with their giant flares like on the Sun (which would be detected later in X-rays by the *Einstein* satellite, Montmerle et al. [14]), inject low-energy ($\sim$MeV) particles necessary to trigger the acceleration process.[3] Second, the accelerated particles would irradiate both the HII region and

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[2] The two other strong sources detected, the Crab pulsar and the mysterious *Geminga*, now identified with the neutron star nearest to the Sun, do not lie in the galactic plane.

[3] This assumption was based on the correlation between the GCR composition with the First Ionization Potential (FIP) in the solar corona. Since then, it has been found that the GCR

the parent molecular cloud (which contains most of the mass). Third, γ-ray emission would take place via the π^o-decay mechanism, just as for the whole galaxy.

The major implication was that, given the γ-ray flux detected from the SNOBs, the *in situ* accelerated cosmic-rays (above ∼1 GeV) would have a flux over one order of magnitude larger than the average galactic flux! In other words, *SNOBs were localized sources of cosmic-rays*. They were too few (probably not more than a few tens at the scale of the whole galactic disk) to be the sources of all GCR, but clearly they had the potential to offer a close-up view of cosmic-ray acceleration processes and their interaction with interstellar matter – already seen on a galactic scale.

The next γ-ray satellite, the *Compton Gamma-Ray Observatory*, or *CGRO*, was launched in 1991, i.e., almost a decade after COS-B ended its mission, and was brought down voluntarily 9 years later. From the point of view of the association of GeV γ-ray sources with SNOB-like sources, it is fair to say that there was not much progress, because galactic γ-ray sources were swamped by hundreds of extragalactic ones (at least, lying at high galactic latitudes), and the spatial resolution of its spark-chamber experiment, *EGRET*, was not so much better than that of COS-B (∼0.5° HWHM at high energies). At least, it was still insufficient to resolve SNOB-like sources, and in fact this essentially is still the case today with *Fermi*.

The real breakthrough came from *HESS*. Although operating at a much higher energy range than the γ-ray satellites, its sensitivity, and above all, its angular resolution, were the decisive factors that contributed to the "revival" of SNOB-like γ-ray sources. Indeed, the typical resolved massive star-forming regions are located at distances 2–3 kpc from the Sun. And at this distance, the ∼0.1° resolution of *HESS* allows to image molecular clouds! Early results of *HESS*, and similar Čerenkov telescopes that followed (MAGIC, VERITAS…) confirmed, beyond doubt, that massive star forming regions hosting a supernova remnant indeed make a well-defined, if not dominant, class of TeV γ-ray sources, many of which have GeV counterparts seen by *Fermi*.

So now, we are at last in a position to scrutinize the acceleration, diffusion and propagation processes of cosmic rays in the vicinity of supernova shocks, the interaction of both high-energy (GeV-TeV) and low-energy (∼100 MeV and below) cosmic rays with molecular clouds, generating high-energy γ-rays and ionization processes respectively. It is clear that such studies go far beyond the "simple" study of these sources, and will have a broader impact on our understanding of high-energy processes at work in the Milky Way at large.

This is all that the present book is about. For the first time, a whole volume gives a fresh, but comprehensive view of this growing topic, written by the best experts. It should be a precious reference source, not only for aficionados that have contributed to the field for 40 years or more, but for all the newcomers (presumably young!). I wish it a great success.

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composition is better correlated with that of interstellar grains, so this part of the SNOB scenario doesn't hold anymore – but the "injection problem" for the diffusive acceleration mechanism remains.

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