

## ASTRONOMY

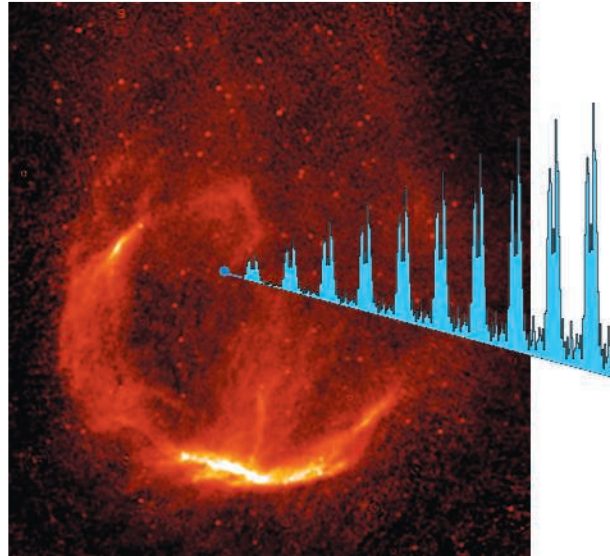
## Gamma Rays and Neutron Stars

Giovanni F. Bignami

Only Galileo was quicker. After discovering the satellites of Jupiter on 10 January 1610 in Padua, he wrote up his results in elegant Latin, personally did the artwork, allowed time for refereeing (by the Inquisition) and for printing (by hand), and had the *Sidereus Nuncius* hit the streets, or the canals, of Venice on 10 March. The NASA-led, international GLAST mission, now called the Fermi Observatory, was launched on 11 June 2008, deployed flawlessly into orbit, started taking in gamma rays from the sky and routing them through an impressive data-crunching machine, allowed time for a minimum of thinking, and just 4 months later, its first important result was reported online [Abdo *et al.*, see p. 1218 of this issue (1)]. Even Galileo would have been impressed, and so should we: Here is a new way of doing science, right on the eve of the International Year of Astronomy.

As Abdo *et al.* report, the Fermi Observatory has—for the first time in gamma-ray astronomy—discovered a rotating neutron star purely through its gamma-ray emission: Fewer than 1000 photons, collected over 2 months, are shown to have a convincing periodicity of about a third of a second. The star is not seen to emit at all at radio and optical wavelengths, and the weak x-ray emissions from the star are not pulsed. In short, Fermi has found a pure gamma-ray star, a “gamstar,” or, if you will, the second Geminga (2). Only, it took 20 years (from 1973 to 1993) to understand the unidentified gamma-ray source that we had called Geminga, and which until today, was the only known rotating gamma-ray neutron star invisible in radio.

The new gamstar, as yet unnamed, is close to the center of CTA1, a diffuse remnant of a supernova that exploded about 10,000 years ago (see the figure). The gamstar’s age, estimated by the slowing of its rotation, is consistent with its being the hard-core remnant of that explosion. A nice, coherent association—if a little déjà vu: It brings to mind the Vela pulsar and the diffuse emission surrounding it, remnants of a supernova explosion that took place around the time of the CTA1 supernova. However, the Vela pulsar is much closer to us



**A new gamstar.** The CTA1 supernova remnant has a well-formed radio shell, with a diameter of about  $1.5^\circ$ . Close to its center, the Fermi gamstar (blue dot) discovered by Abdo *et al.* (1) emits trains of pulsed gamma radiation.

and could be observed at the dawn of gamma-ray astronomy in 1975 (3), using radio data to clock the sparse gamma-ray photons. In fact, scientists continued to find gamma-ray pulsars using radio data, with the remarkable, if laborious, exception of Geminga. Fermi’s little brother, the Italian gamma-ray mission AGILE, has just found another Vela-like gamma-and-radio pulsar (4), the sixth of its kind.

Herein lies the importance of the Fermi gamstar discovery: From now on, given half-decent photon statistics, no radio data will be required for finding pulsating gamma-ray sources. Known gamstars, now numbering two, are not only here to stay but are likely to quickly increase in number.

A third one may already be coming up: a previously discovered gamma-ray source officially called 3EG J18335+5918, which Jules Halpern (co-discoverer of Geminga) has called the “next Geminga.” This gamma-ray source lacks a radio counterpart, but otherwise has all the markings of a neutron star. AGILE has now found interesting time variability for the source (5). CTA1 ended up being the real “next Geminga,” but this one may be next in line.

Many more Geminga-like gamstars may soon be discovered by Fermi (and AGILE) by looking at the position of unidentified gamma-ray objects (UGOs), which represent the

Satellite and ground observations provide new insights into gamma-ray emissions from neutron stars.

majority of known gamma-ray sources in our Galaxy. Interpreting UGOs as gamstars would provide a natural explanation for the quarter-of-a-century UGO mystery: Gamstars are simply pulsars that emit gamma rays in a fan beam geometrically different from the radio one, which may well exist but does not intercept the Earth. Gamstars would then be neutron stars with a somewhat different physics (and geometry) from that of the gamma-and-radio pulsars (like Vela and the Crab), for which both beams sweep the Earth.

But neutron stars and gamma rays seem to have even more in common. On page 1221 of this issue, The MAGIC Collaboration (6) shows that the Crab pulsar—our prototype of the well-behaved neutron star, known to judiciously emit pulsed radiation from radio photons to gigaelectron volt (GeV) gamma rays—reaches its peak emission energy at 25 GeV and quickly fades afterwards. This is a brilliant result of the MAGIC Collaboration, who lowered the energy threshold of their ground-based telescope to around 25 GeV and for the first time detected pulsed gamma rays from the Crab at that energy.

Detecting 25 GeV gamma rays from the ground requires careful discrimination between signal and noise. By doing so, the authors bridged the decade-long gap between ground- and space-based gamma-ray astrophysics, because the upper energy limit of Fermi photons will be close to 20 GeV. Since the 1970s, gamma-ray energies detected from the Crab have increased from tens of MeV (7) to several GeV (8, 9), and now 25 GeV from MAGIC—an increase by an energy decade per calendar decade.

The MAGIC data show that even young neutron stars, like the Crab, less than 1000 years old, have their limitations in producing higher and higher energy photons. Above 25 GeV, MAGIC sees a sharp cut-off in the Crab spectrum. This has immediate implications for neutron star physics, because it discrimi-

nates between models that have competed, unchecked, for decades. Models in which gamma rays are produced near the outer gap of pulsar magnetosphere, far from the neutron star surface, appear best suited to explain the MAGIC data.

To prove theoreticians wrong or right is but a small satisfaction to the observer, who strives to see the unseen. Galileo and Fermi,

who excelled both in theory and observations, would have loved to explore the new horizons opened up by gamma rays and neutron stars working together to teach us something new.

#### References

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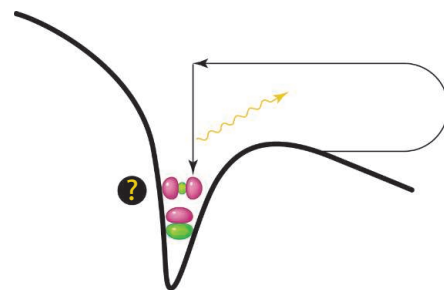
## CHEMISTRY

# Interrogating Molecules

Gilles Doumy and Louis F. DiMauro

The study of chemical reactions in real time (1) has been a major success of lasers capable of generating light pulses shorter than several tens of femtoseconds ( $1 \text{ fs} = 10^{-15} \text{ s}$ ). Facilitated by the discovery of the strong-field phenomenon of high harmonic generation (HHG) (2, 3), these pulses now promise to let us observe the electron dynamics inside an atom or a molecule, which occur over an even shorter time scale: tens of attoseconds ( $1 \text{ as} = 10^{-18} \text{ s}$ ). On pages 1232 and 1207 in this issue, McFarland *et al.* (4) and Li *et al.* (5) show how it is possible to use HHG selectively for probing different molecular orbitals, thus meeting a necessary condition for studying the internal dynamics of complex molecular systems.

To understand the complex interplays at work in the two studies, consider what happens to an atom or a molecule subjected to an intense laser field with a magnitude comparable to that of the Coulomb field that binds the electrons to the nucleus. Such conditions ("strong-field physics") are readily accessible with, for example, femtosecond-based titanium-sapphire laser systems. Most of the relevant physics can be explained by a simple three-step model (6, 7) (see the figure). First, the laser field suppresses the potential barrier, thereby allowing quantum tunneling to free the electron from the nucleus. Second, the freed electron is accelerated by the laser field and is either completely ionized or, after approximately one-half of an optical cycle, is accelerated back toward the parent ion. Third, the returning field-accelerated electron may recombine with the parent ion and emit a very short (attosecond duration) burst of soft x-rays. Because this process



**Three-step model.** An electron can tunnel out of the suppressed potential barrier and come back accelerated by the field. It can recombine to emit x-ray photons. It is now possible to select which molecular orbital is involved in this process.

occurs every half optical cycle, the signature of this emitted radiation is a spectral comb of odd-order high harmonics of the fundamental field frequency.

Since the discovery of this process, most studies have concentrated on improving such properties of HHG as bandwidth, number of photons, and duration of the attosecond bursts. However, it became apparent that those properties were extremely dependent on the specific target, typically dense gas jets, used for the generation. Thus, HHG not only provides a unique opportunity to study laser-matter interactions in the strong-field regime, but can also be used as a probe of the generating system itself. Furthermore, the sensitivity of the process to variations faster than an optical cycle provides a probe of unmatched temporal resolution.

The dependence on the generating medium is particularly important for molecules, because molecular symmetry and rotational-vibrational dynamics make for richer physics (8). An important demonstration with nitrogen ( $\text{N}_2$ ) as the generating medium introduced a new method that allowed for the tomographic reconstruction of the molecular

orbital involved in the HHG process (9). By measuring the HHG spectrum from the  $\text{N}_2$  molecules as a function of the angle between the laser polarization and the molecular axis, the static highest occupied molecular orbital (HOMO) describing the original electronic state involved in the HHG process was reconstructed. However, realizing the full potential of HHG tomography in the time domain requires a probe of the multiple orbitals involved in the dynamics. The two studies in this issue directly address this challenge by showing that HHG is indeed capable of providing information on different orbitals, provided that one "interrogates" the system in the correct way: By modifying the "configuration" of the molecule (orientation or bond length), HHG preferentially involves either the HOMO or the orbital immediately below it, called HOMO-1.

McFarland *et al.* investigated the HHG emission of different harmonic orders for  $\text{N}_2$  molecules. The molecular alignment was controlled by another lower-intensity short-pulsed laser that induced alignment along its polarization axis (10). The alignment of the molecular axis relative to the polarization of the HHG generating field (e.g., perpendicular or parallel) can then be controlled by adjusting the delay between the two laser pulses. When measured as a function of this delay, the highest-order harmonics displayed a peculiar behavior: a decreased signal when parallel, and an increased signal when orthogonal. They explained this behavior by involving HHG from the HOMO-1 on top of the expected generation from the HOMO.

Li *et al.* approached the problem differently by studying HHG from  $\text{NO}_2$  dimers. The weak N-N bond was first nonresonantly excited by an ultrashort pulse. By introducing a variable delayed HHG generating pulse, they studied the influence of the bond length

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