Future Gamma-Ray Observations of Pulsars and their Environments

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Summary. Pulsars and pulsar wind nebulae seen at gamma-ray energies offer insight into particle acceleration to very high energies under extreme conditions. Pulsed emission provides information about the geometry and interaction processes in the magnetospheres of these rotating neutron stars, while the pulsar wind nebulae yield information about high-energy particles interacting with their surroundings. During the next decade, a number of new and expanded gamma-ray facilities will become available for pulsar studies, including Astro-rivelatore Gamma a Immagini LEggero (AGILE) and Gamma-ray Large Area Space Telescope (GLAST) in space and a number of higher-energy ground-based systems. This review describes the capabilities of such observatories to answer some of the open questions about the highest-energy processes involving neutron stars.

1 Motivation: the role of gamma rays

Gamma rays are produced by nonthermal processes, often involving high-energy particles. Any aspect of a neutron star system that accelerates particles is therefore a potential source of gamma rays. As the example of Fig. 1 shows, both the Crab pulsar itself and the pulsar wind nebula can produce high-energy particles that interact to create gamma rays. In the case of the Crab, the highest-energy emission from the pulsar is seen in the GeV energy band, while the pulsar wind nebula yields gamma rays up to TeV energies. These gamma rays are probes of the primary interaction processes of the energetic particles.

Other reviews in this volume have discussed the details of the open issues involving gamma-rays from pulsars and pulsar wind nebulae. These include:

- Where and how are particles accelerated?
- How do the particles interact? With what do the particles interact?
- Are the processes the same for all neutron star systems?
- How does the complex environment (frame dragging, aberration, strong magnetic and electric fields, high currents) produce the observed radiation patterns?

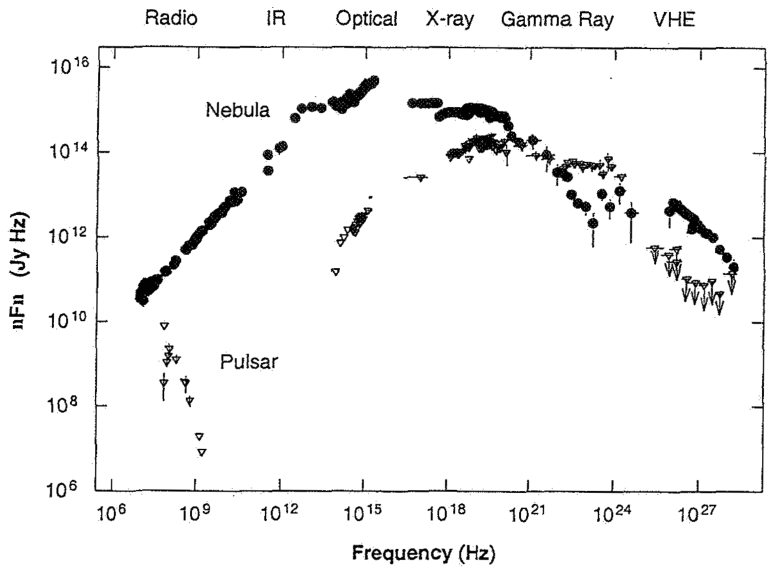

Fig. 1. Crab pulsar (open triangles) and nebula (filled circles) spectral energy distributions. The original compilation of data was done by Bartlett [1]. Data sources for the nebula: radio [2], IR [3], [4], [5], [6], Optical [7], UV [8], X-ray [9], [10], [11], Gamma ray [12], TeV [13]. Data sources for the pulsar: radio [14], [15], [16], IR [17], Optical [18], UV [19], X-ray [20], [10], [21], Gamma ray [22], TeV [23], [24], [13].

The last of these questions is crucial. The complexity of neutron star systems guarantees that no simple observations of a few systems can answer these fundamental questions. Experience with two generations of gamma-ray telescopes has not produced a consensus on even the basic issues.

2 Using observations

From an observer's point of view, there are two broad approaches to the future study of high-energy emission from neutron stars:

1. Observation-driven questions
   - What patterns seen in present data will survive with better observations?
   - What are the implications of such patterns?
2. Theory-driven questions
   - What predictions of current models will be borne out by new observations?
   - How will theoretical models evolve in response to improved data?

2.1 Status of observations

The current status of observations of gamma-ray pulsars was reviewed by Thompson [26] and is summarized in other articles in this volume. Some of the issues raised by observations are:

- All the brightest pulsars seen by EGRET have light curves with two peaks, in strong contrast to the scarcity of double pulses in the radio. Do these light curves imply that gamma-ray pulsars have a particular combination of beam pattern and observing angle?
- All known gamma-ray pulsars have a high-energy spectral cutoff, and the cutoff energy seems to decrease for pulsars with stronger magnetic fields. Does this pattern reflect fundamental pulsar physics, or could it be an apparent pattern due to the limited statistics?
- The integrated high-energy (> 1 eV) luminosity of the gamma-ray pulsars shows a trend increasing with open field line voltage. How does the luminosity change at lower voltages, where the luminosity would approach the total available spin-down energy? How much does the assumption of 1 steradian beaming angle affect this apparent trend?

2.2 Status of theory

Other papers in this volume summarize the theoretical situation well. In particular, the polar cap, slot gap, and outer gap models can all reproduce the observed double-pulse light curves of gamma-ray pulsars. Theories do make a variety of predictions testable with new gamma-ray telescopes. Some of these will be discussed in a later section.

3 Future ground-based observatories

The third generation of ground-based gamma-ray observatories has emerged in recent years and continues to evolve. All such observatories operate at very high energies (VHE), typically above 100 GeV, using the Earth's atmosphere as a detector and viewing the Cherenkov light or particle showers produced by the interactions of the gamma rays at high altitudes. This field is progressing rapidly. The reader is encouraged to consult Web sites listed in this report for current information.

3.1 CANGAROO-III

CANGAROO-III (Collaboration of Australia and Nippon for a GAmma Ray Observatory in the Outback) is one of four major Atmospheric Cherenkov Telescopes (ACT). It consists of four 10-meter telescopes that collect the light from flashes of Cherenkov radiation produced by very high energy gamma-ray interactions [25]. CANGAROO-III is a joint Australian-Japanese collaboration, with the telescopes located in Australia. Their Web page is *http://icrhp9.icrr.u-tokyo.ac.jp/*. Fig. 2 shows the four telescopes.

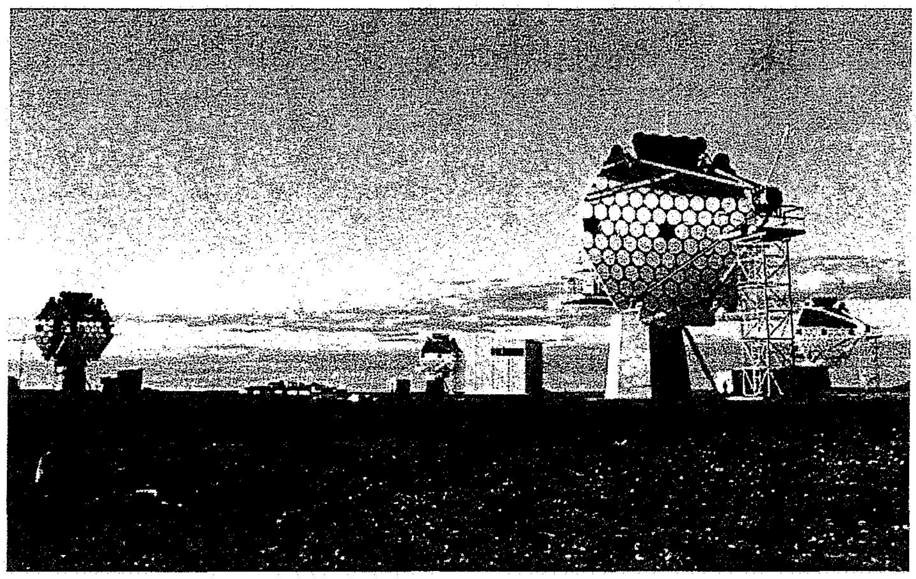

Fig. 2. CANGAROO-III telescope array.

The telescopes were cleaned and refurbished in the Fall of 2005, and CANGAROO-III is now taking data, including observations of neutron star systems. With the improvements over earlier CANGAROO telescopes, the group sees the Crab and finds evidence for some other supernova remnants, but they do not confirm the earlier claims for emission from SN 1006 and PSR B 1706−44 [25]. Future plans include an upgrade to the oldest of the four telescopes.

3.2 H.E.S.S.

H.E.S.S. (High Energy Stereoscopic System) is an array of four 12-meter telescopes located in Namibia (Fig. 3). Overviews of H.E.S.S., which is an international collaboration with a European emphasis, can be found at International Cosmic Ray Conferences [27], [28]. Their Web page is *http://www.mpi-hd.mpg.de/hfm/HESS/*.

As of mid-2006, H.E.S.S. is the most advanced ACT, having been in full operation with four telescopes for nearly two years. Results involving neutron star systems include:

- Pulsar wind nebulae such as MSH 15−52, seen as extended TeV sources [33]

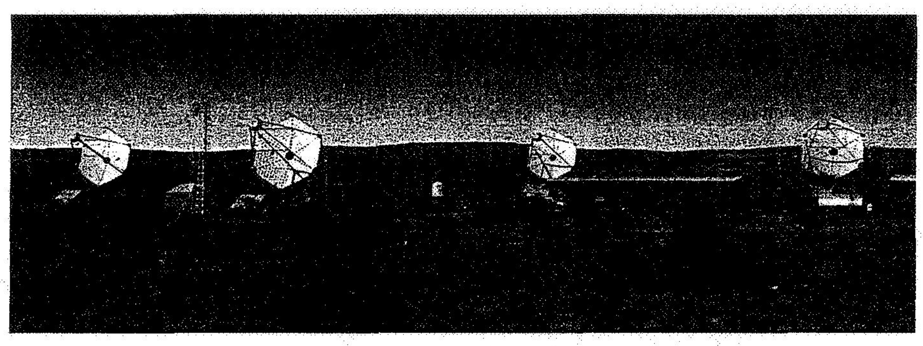

Fig. 3. H.E.S.S. telescope array.

- TeV emission from the binary system of PSR B1259−63, showing variation with orbital phase [30]
- VHE radiation from the X-ray binary, microquasar system LS 5039 (although the companion object could be a black hole instead of a neutron star) [31]

In all cases, particles are thought to be accelerated to high energies by shocks. No pulsed emission has been seen.

Planning is currently under way for a major addition to H.E.S.S. The H.E.S.S. Phase II array will include a single 27 m telescope located in the middle of the present array [32]. An artist's concept is shown in Fig. 4. This addition will more than double the total collecting area of the array and will allow measurements down to lower energies, with a threshold approaching 20 GeV. The new telescope is expected to be complete in 2008.

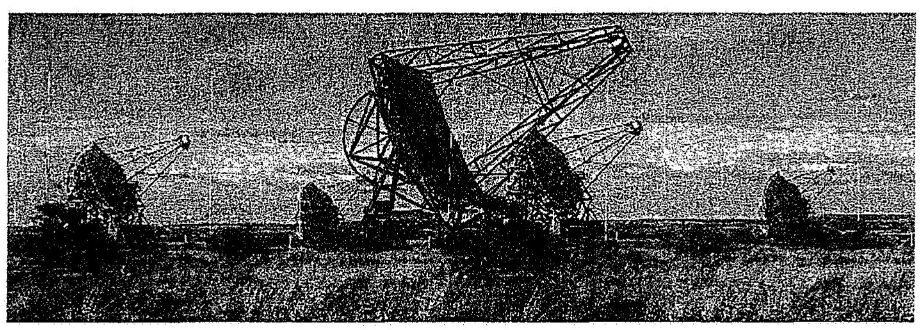

Fig. 4. Plan for H.E.S.S.-II array.

3.3 MAGIC

MAGIC (Major Atmospheric Gamma-Ray Imaging Cherenkov) is a single 17 m Air Cherenkov telescope located at La Palma in the Canary Islands (Fig. 5) [34]. Like HESS, the international collaboration that built and operates MAGIC is predominantly European. Their Web page is *http://wwwmagic.mppmu.mpg.de/*.

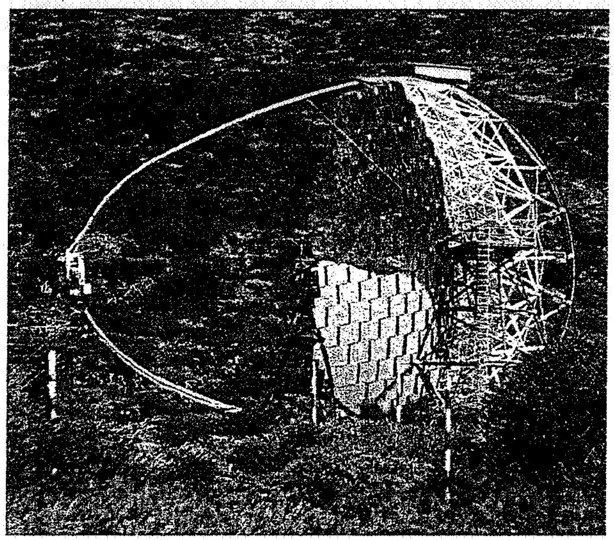

Fig. 5. MAGIC telescope, currently in operation.

Among other results, MAGIC has seen variable, possibly periodic, TeV emission from a northern microquasar, LSI +61 303, which contains a compact object (black hole or neutron star) [35].

Currently under construction is a second identical telescope for MAGIC, located 85 m from the original telescope (Fig. 6). With the additional collecting area and stereoscopic capability, MAGIC is expected to push its operating threshold much lower, close to 20 GeV.

3.4 VERITAS

VERITAS (Very Energetic Radiation Imaging Telescope Array System) is the successor to the pioneering Whipple Observatory ACT, which is continuing operations. The first of four 12 m VERITAS telescopes has been in operation since 2005 [36], and a second telescope has recently started operation (Fig. 7) [37]. The collaboration is international, with prominent U.S. and Irish contributions. Their Web page is *http://veritas.sao.arizona.edu/*.

Although the VERITAS collaboration has encountered problems in finding a suitable site for VERITAS acceptable to local interests, plans are moving

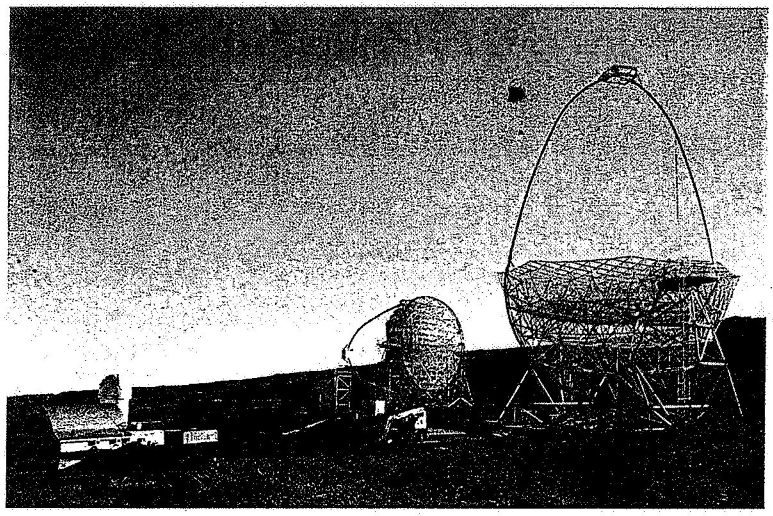

Fig. 6. The two MAGIC telescopes. MAGIC 2 is still under construction, with completion expected in 2007.

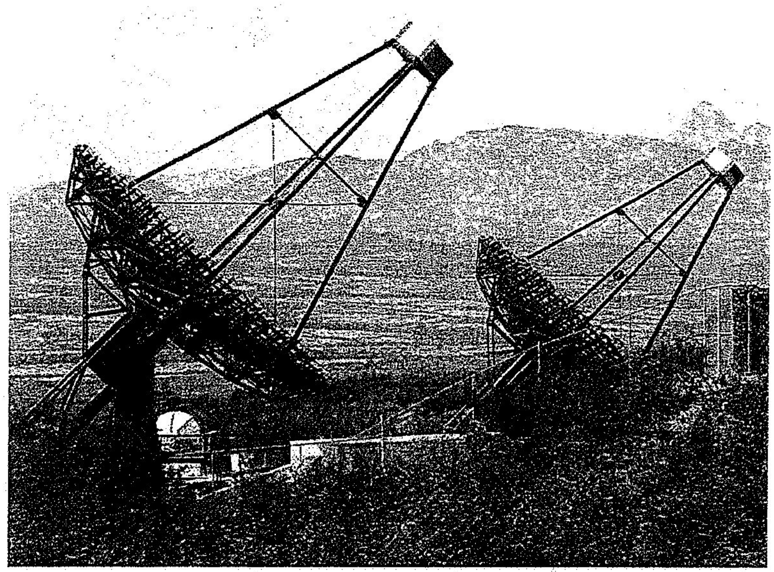

Fig. 7. VERITAS two telescope system.

ahead for a four-telescope system (Fig. 8), with an ultimate goal of seven telescopes [38].

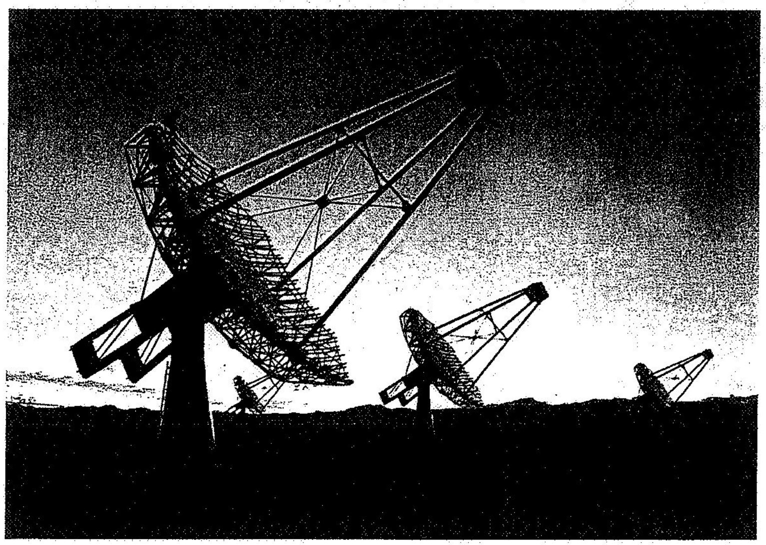

Fig. 8. Artist's concept of the VERITAS 4 telescope system.

3.5 Wide-field VHE telescopes

Two TeV telescopes under development will have wide fields of view, seeing most of the sky from their locations. Although such telescopes typically have less sensitivity for individual sources than the ACTs, the wide-field instruments can perform surveys and detect transients. They are:

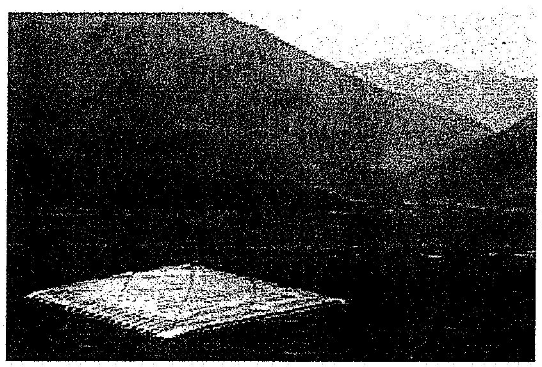

Fig. 9. Artist's concept of Mini-HAWC at a high-altitude location.

Fig. 10. The ARGO-YBJ facility in Tibet.

- Mini-HAWC (High-Altitude Water Cherenkov) is a concept based on moving the detectors from the successful Milagro Observatory [39] to a high-altitude site (Fig. 9) [40]. Site selection is underway, and the Milagro hardware is in operation.
- ARGO-YBJ (Astrophysical Radiation with Ground-based Observatory at YangBaJing) is a shower-detection system based on resistive plate chambers [41]. Much of the construction at the site in Tibet is complete (Fig. 10), preliminary data are available, and the system should be complete within the next year [42].

3.6 Neutron star science with future VHE observatories

Thanks to the developments just described, the future of ground-based gamma-ray instrumentation will be a world-wide assembly of telescopes with substantially higher sensitivity and resolution than those of the previous generation. Historically, any large increase in telescope performance has produced astrophysical surprises, making predictions of what will be seen somewhat risky. Nevertheless, the current results, particularly those of H.E.S.S., point toward some likely prospects.

Pulsed emission

As results presented at this conference confirm, there are still no detections of pulsed emsission from ground-based gamma-ray telescopes. A summary is given by Schmidt [43]. EGRET did, however, see evidence for pulsed emission from five pulsars at energies above 10 GeV [44]. As the newer ground-based telescopes, especially MAGIC 2 and H.E.S.S.-II, push down their effective energy thresholds, they should have a good chance to see the tail of the pulsed emission, depending somewhat on the detailed shape of the cutoff above 10

GeV. The huge collecting areas of ground-based telescopes complement the direct measurements from satellite detectors, which are photon limited at the highest energies. The upper limit of pulsed radiation is an important parameter to constrain the particle acceleration and gamma-ray production mechanisms in pulsar magnetospheres.

One nearly-inevitable consequence of outer gap pulsar models is that high-energy electrons in the outer gap will inverse Compton scatter infrared photons up to TeV energies [45], [46], although the predicted flux is model-dependent. The H.E.S.S. upper limits for the Vela pulsar [43], shown in Fig. 11, begin to constrain some models [47], although this is not the case for the other pulsars observed by H.E.S.S. With more observations by all the coming TeV telescopes, these upper limits can be expected to improve, possibly offering challenges that may require revisions to outer gap models.

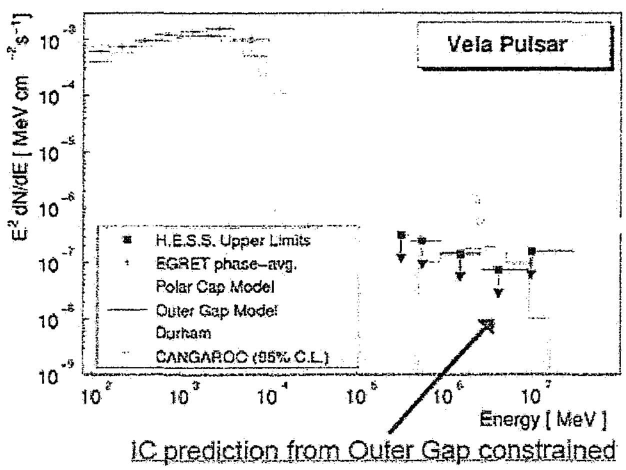

Fig. 11. H.E.S.S. pulsed limits for Vela [43]

Pulsar wind nebulae and related phenomena

Objects with shock-accelerated particles interacting to produce TeV gamma rays have become a major source class, particularly due to the H.E.S.S. Galactic Plane survey [48] and follow-on observations. Fig. 12 shows a recent example, the "Kookaburra" region [49]. HESS J1420−607 appears to be the pulsar wind nebula (PWN) associated with PSR J1420−6048. HESS J1418−609 seems related to an X-ray nebula. Although no radio pulsar is seen, it seems likely that this is also a PWN. The fact that most of the H.E.S.S. sources in the Galactic Plane are extended suggests that many are this same phenomenon.

Such sources seen by H.E.S.S. and the other third-generation TeV telescopes may lead to new PWN and possibly new pulsar detections. Multiwavelength modeling (see the review by DeJager in these proceedings) should lead to new insight into the particle acceleration taking place in these pulsar winds.

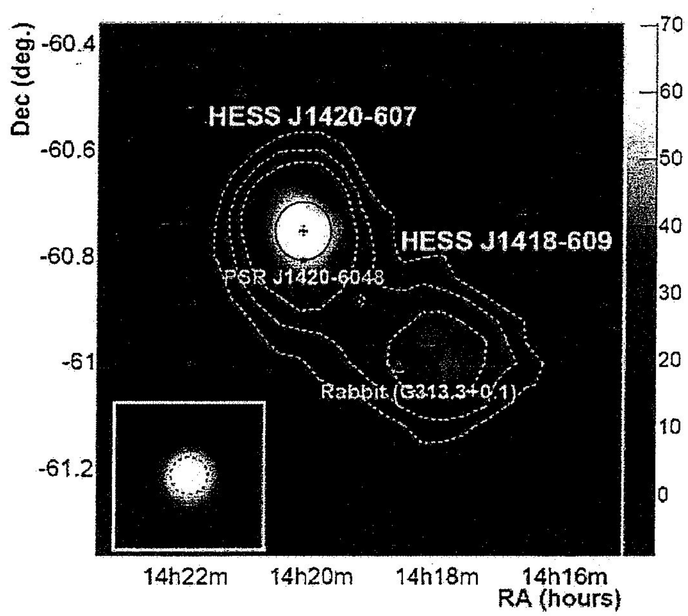

Fig. 12. H.E.S.S. pulsar wind nebula sources in the "Kookaburra" region [49]

4 Future space-based observatories

At lower gamma-ray energies, the atmospheric shower detection technique becomes increasingly difficult. Space-based observatories provide measurements that are complementary to the gound-based telescopes in terms of energy and sensitivity. Two such observatories are scheduled for launch within the next two years.

AGILE

AGILE (Astro-rivelatore Gamma a Immagini LEggero) is an Italian satellite now in the final stages of preparation for launch (Fig. 13) [50]. Their Web site is *http://agile.rm.iasf.cnr.it/index.html*. AGILE is planned as a two-year mission.

Spaceborne high-energy gamma-ray detectors rely on direct detection of the pair production interaction. Like the earlier SAS-2, COS-B, and EGRET detectors, AGILE has a tracker to convert the gamma rays and determine the arrival direction (silicon strips instead of the older gas detectors), a calorimeter to measure energies (cesium iodide), and an anticoincidence detector to reject the huge background of charged particles in space (plastic scintillator).

AGILE's high-energy detector will operate in the energy range 30 MeV to 50 GeV. It has a very large field of view (approx. 2.5 ster) and will therefore map a large fraction of the sky for each pointing direction. Although physically smaller than EGRET on the Compton Observatory, AGILE will have comparable source sensitivity and angular resolution. AGILE also has a thin, lightweight coded mask X-ray imager (called super-AGILE).

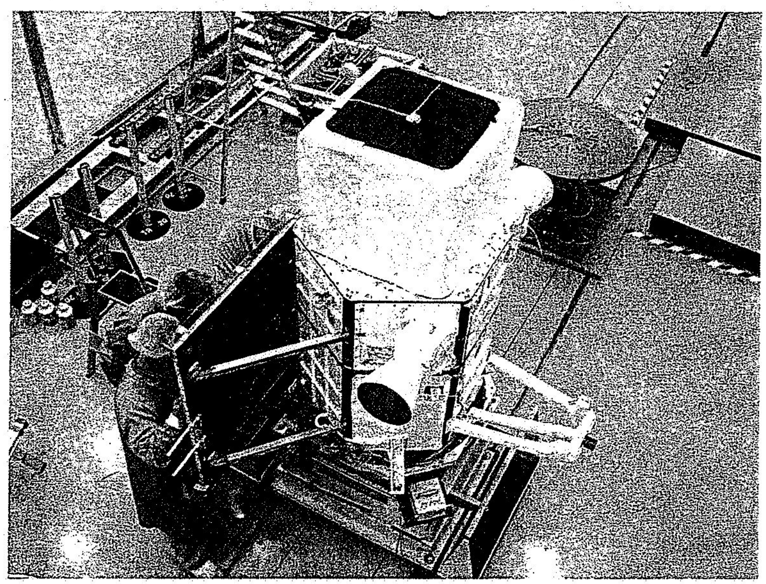

Fig. 13. The AGILE telescope and spacecraft

Neutron Star Science with AGILE

With its excellent timing capability, AGILE will be well-suited to resolving some of the gamma-ray pulsar questions that emerged from the Compton Observatory mission. These questions fall into two areas:

- Will AGILE confirm the EGRET measurements of pulsed emission from PSR B0656+14, PSR B1046−58, and PSR J0218+4232 (Fig. 14)? Although promising, the confidence levels that the EGRET data are pulsed are about 5 orders of magnitude lower than those of the best-known gamma-ray pulsars [26]. PSR J0218+4232 is of particular interest, because it is the only ms pulsar for which evidence is seen in gamma rays.

- Will AGILE detect puled gamma radiation from any of the newly-discovered radio pulsars located in EGRET unidentified source error boxes? Such pulsars as PSR J1016−5857, PSR J1015−5719, PSR J1420−6048, PSR J1637−4642, PSR J1837−0559 and PSR J2229+6114 were discovered after the end of the Compton Observatory mission and have spin-down luminosities large enough that a few percent of their energy losss could power the gamma-ray emission [51], [52]. Due to timing uncertainities and the possibility of glitches, extrapolation back to the EGRET data is not efficient [53]. By detecting these, AGILE could significantly expand the sample of gamma-ray pulsars.

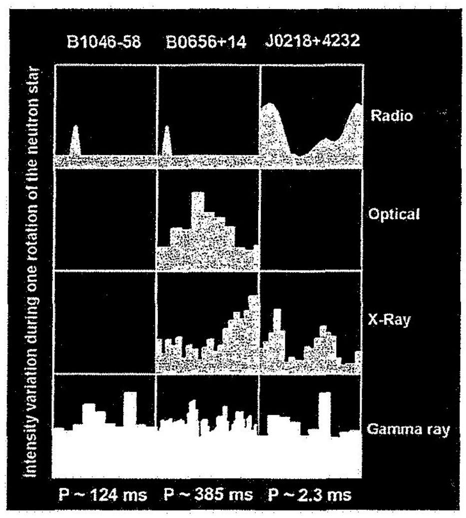

Fig. 14. Multiwavelength light curves of three lower-confidence gamma-ray pulsars that can be tested by AGILE [26].

GLAST

GLAST (Gamma-ray Large Area Space Telescope) is currently under construction and planned for a launch in the Fall of 2007. GLAST is designed as a major international facility with a minimum lifetime of five years. The mission Web site is *http://glast.gsfc.nasa.gov/* The GLAST Observatory will carry two scientific instruments (Fig. 15):

- The GBM (GLAST Burst Monitor) is a successor to BATSE on the Compton Observatory. It will use a set of sodium iodide (NaI) and bismuth germanate (BGO) wide-field detectors to monitor the sky for transients in the 10 KeV – 30 MeV energy range (Fig. 16) [54]. The GBM will be

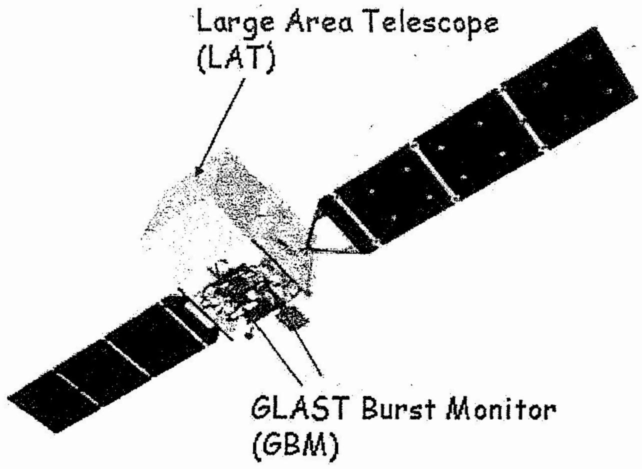

Fig. 15. The GLAST Observatory, showing the two instruments.

able to detect soft gamma repeaters, but it does not have a pulsar timing mode.

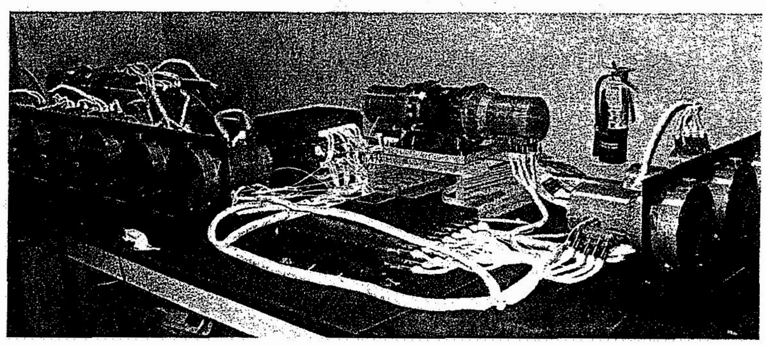

Fig. 16. The GLAST Burst Monitor flight hardware.

- The LAT (Large Area Telescope) is the primary instrument on GLAST. The LAT, which was called GLAST by itself in the early phases of the program, is a pair-production high-energy telescope successor to EGRET on CGRO. It uses the same basic technology as AGILE (silicon strip tracker, CsI calorimeter, plastic scintillator anticoincindence detector) but on a much larger scale (Fig. 17) [55]. For neutron star science, the LAT will be the principal GLAST instrument.

Some important characteristics of the GLAST LAT are:

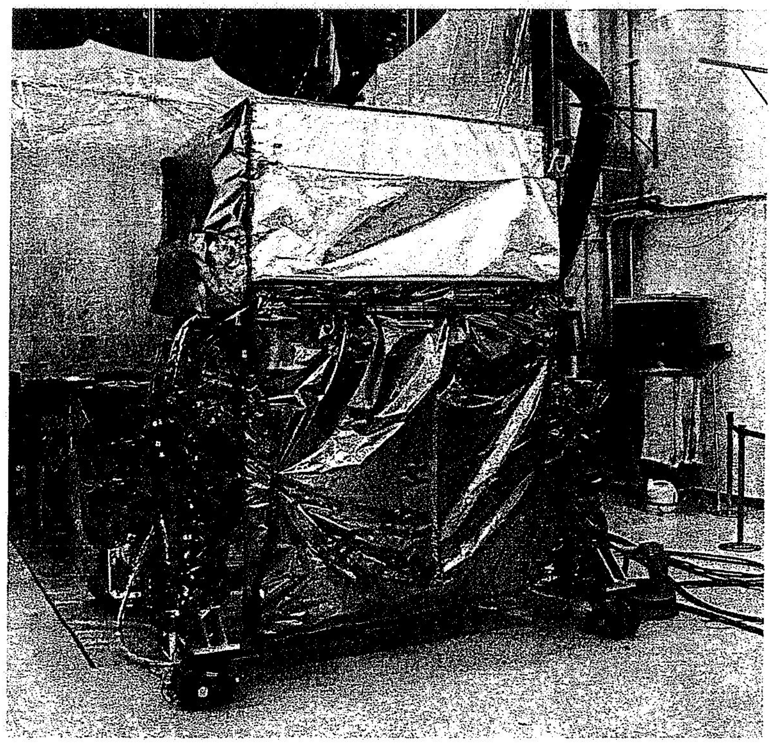

Fig. 17. The GLAST Large Area Telescope with its radiators attached.

- Huge Field of View (~20% of the sky).
- Planned scanning mode views the entire sky every day.
- Broadband (30 MeV - >300 GeV, including the largely unexplored 10 - 100 GeV range).
- Improved Point Spread Function for gamma rays (a factor >3 better than EGRET for E >1 GeV).
- Large effective area (factor >4 better than EGRET).

This combination of improvements results in a factor >30 improvement in sensitivity, with an even larger factor at energies above 10 GeV.

Neutron star science with GLAST - pulsars

Although the final instrument response functions and analysis tools for the LAT are still in development, it is possible to estimate the LAT performance based on its design characteristics [55]. To first order, detecting pulsed gamma radiation is limited by photon statistics (although pulse shape, diffuse gamma-ray backgrounds, spectral shape, and proximity of strong sources affect the ultimate performance). In two years with its scanning mode, LAT will detect

25-30 times as many photons for most pulsars as EGRET did in its lifetime. This improvement results in detections intrinsically 25 times fainter or 5 times farther away. Several of the known gamma-ray pulsars are at distances of 2 kpc; therefore LAT will be able to detect some pulsars at the distance of the Galactic Center or farther.

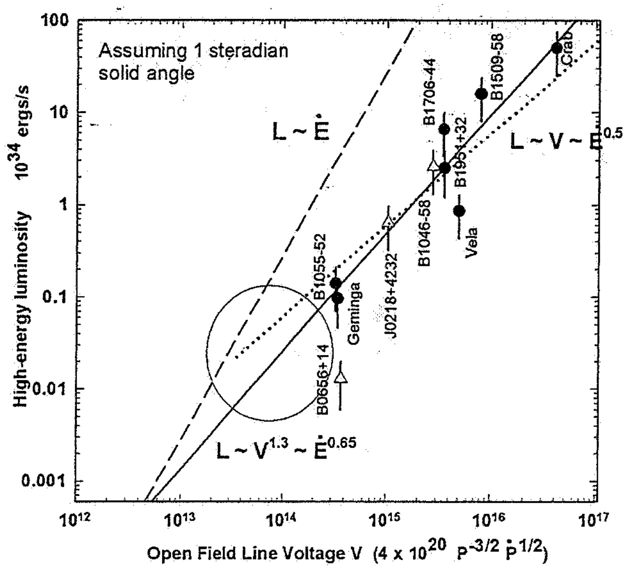

Fig. 18. High-energy pulsar luminosity L vs. open field line voltage V, for high-confidence gamma-ray pulsars (filled circles) and lower-confidence gamma-ray pulsars (open triangles). Solid line: linear fit to the data points. Dotted line: predicted relationship, L $\sim \dot{E}^{0.5}$. Dashed line: total luminosity available from $\dot{E}$ for the same beaming assumption. Circle: new region to be explored by GLAST LAT.

Fig. 18 illustrates one way this expanded sensitivity range affects gamma-ray pulsar studies. The figure shows the relationship between integrated X-ray plus gamma-ray luminosities and open field line voltage for the known gamma-ray pulsars [26]. This trend is fairly linear over several orders of magnitude and is consistent with a pattern of L $\sim \dot{E}^{0.5}$ (dotted line) expected for pulsar models, e.g. [56]. A fit to the data (solid line) produces a relationship proportional to $\dot{E}^{0.65}$, but the uncertainties and the limited statistics do not allow a clear distinction between the two possibilities. If this trend continues to lower luminosities, the circle shows the new phase space that the LAT could study. In particular, data from LAT will test this paattern and address several questions:

- Does this trend continue with a larger number of pulsars?
- What happens to this trend as the observed luminosity approaches the limit of the full spin-down luminosity of the pulsar?
- Does the trend follow the theoretical prediction or the empirical fit?

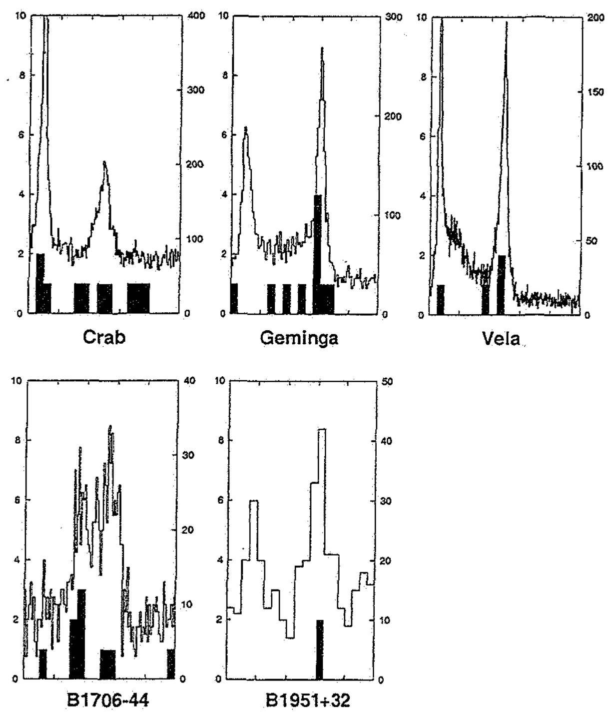

Fig. 19. EGRET pulsar light curves [44]. Lines: E $>\sim$100 MeV (photon counts on the right scale). Solid histograms: E > 10 GeV (photon counts on the left scale). The GLAST LAT will produce light curves above 10 GeV with $\sim$ 100 times the EGRET statistics.

A second important contribution by the LAT will come at the highest pulsar energies. Although EGRET did see emission above 10 GeV, the statistics were minimal (Fig. 19). Nevertheless, there are indications that the light curves at these energies are dominated by one of the two pulses. Above 10 GeV, the LAT will have nearly two orders of magnitude greater sensitivity than EGRET, so the numbers of photons at these energies will be in the hundreds for each pulsar, allowing detailed measurements of the light curves and energy spectra at the highest energies. The shape of the spectral cutoff is an important test of pulsar models.

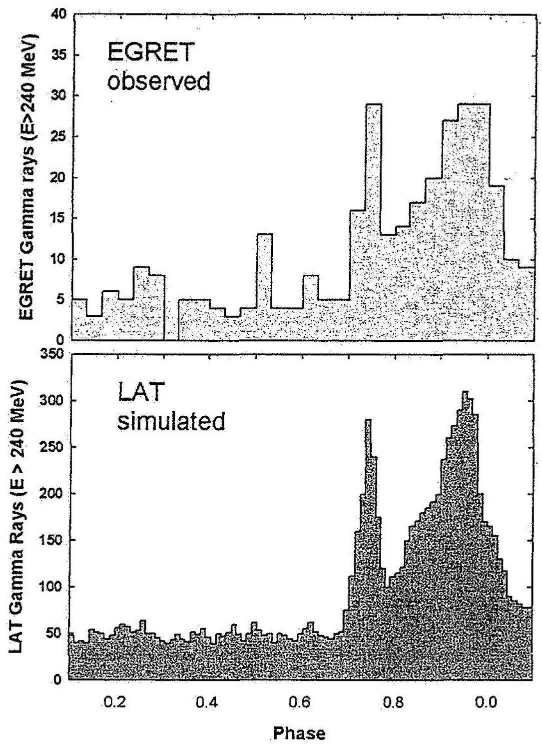

Fig. 20. Gamma-ray light curve for PSR B1055−52. Top: EGRET observed. Bottom: LAT simulated, assuming two years in scanning mode.

A significant constraint in using the EGRET data for testing of pulsar models has been the statistical limitations. Fig. 20 illustrates the level of improvement expected with LAT for a weak EGRET pulsar, PSR B1055−52. Although clearly pulsed, the EGRET light curve has too few photons to allow detailed measurements. The LAT simulation assumes a light curve shape, not based on any particular model, but containing the number of photons expected in two years of scanning. The smaller phase bins and higher counts per bin in the LAT light curve will allow such measurements as the shapes of the pulses, the separation of the pulses, and a determination of whether the emission away from the pulses is associated with the pulsar. Polar cap, slot gap, and outer gap models make distinctive prredictions about these elements of the light curve (see reviews by Harding and Cheng in these proceedings). In particular, pulsar emission at all phases, even beyond the peaks in the light curve, is more likely in a slot gap model, while an outer gap model predicts little emission in the regions away from the pulse.

Millisecond pulsars represent a good illustration of how the GLAST LAT will facilitate observational tests of theoretical predictions. Although ms pulsars are far older and have much weaker magnetic fields than most of the pulsars seen in gamma rays, their short periods imply open field line voltages that are similar to those of the young gamma-ray pulsars. In principle, therefore, ms pulsars can accelerate particles to the high energies needed for gamma-ray production. The best case for gamma-ray emission from a ms pulsar is PSR J0218+4232 [57], whose gamma-ray light curve resembles that seen in the X-ray band, although without extremely high statistical significance. By contrast, EGRET found no evidence for emission from ms PSR J0437−4715 [58], a bright X-ray pulsar only 139 pc distant (compared to 5.7 kpc for PSR J0218+4232), nor was any indication of a gamma-ray excess seen from the direction of 47 Tuc [59] despite the presence of more than 20 ms pulsars in this globular cluster.

Fig. 21 shows predictions of ms gamma-ray pulsar emission above 100 MeV for one polar cap model [60]. The vertical bars show the effect of a range of possible particle injection energies; the primary gamma-ray production process is curvature radiation. The dashed line represents the nominal GLAST LAT limiting high-latitude sensitivity for two years of scanning (the limit would be higher closer to the Galactic Plane due to higher background). The model prediction for PSR J0218+4232 is well below the flux implied by the EGRET result of [57]. In this model, the LAT would be expected to see a few ms pulsars, including PSR J0437−4715.

Fig. 22 is based on an outer gap model [61] in which the primary source of gamma rays is the synchro-curvature radiation process. The heavy data points added to the figures are from EGRET. The model prediction lies nearly an order of magnitude below the EGRET data points for PSR J0218+4232. With its improved sensitivity, the LAT should be able to detect and meaure spectral properties of both PSR J0437−4715 and PSR J0218+4232. LAT detections of PSR B1821−24 and PSR J2124−3358 are also predicted by this model.

Fig. 23 shows spectra for two ms pulsars in another polar cap model [62]. In this model, cyclotron resonant absorption of radio emission offers an explanation of the EGRET results for PSR J0218+4232. Other ms pulsars, including PSR J0437−4715 shown in this figure, are expected to produce curvature radiation at a level below the EGRET threshold but visible to LAT. One possible problem with this model is that it also predicts that some other ms pulsars, including those in 47 Tuc, should have been seen by EGRET.

Although these three examples are not a comprehensive review of ms pulsar theory, they highlight the differences in spectral and population properties for different models. Thanks to the extensive theoretical work on various mod-

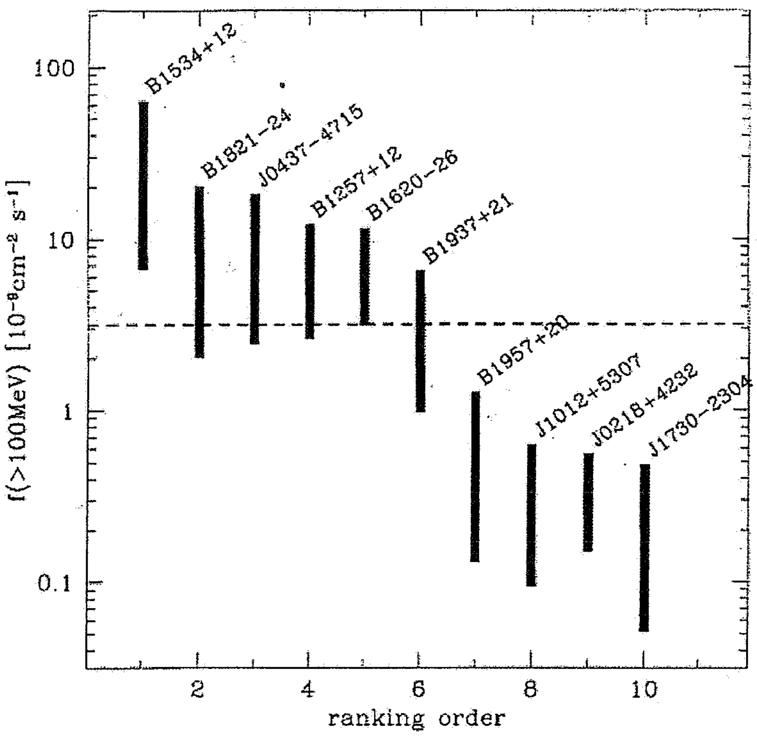

Fig. 21. Predictions of from one polar cap model of ms pulsars [60]. The dashed line represents the nominal GLAST LAT threshold for high-latitude sources after two years of scanning.

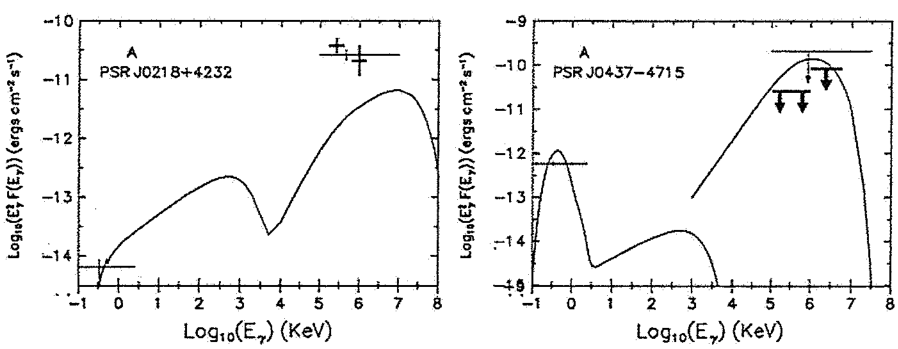

Fig. 22. Predictions from an outer gap model for ms pulsars. Original figures from [61], with EGRET data and upper limits added (heavy data points).

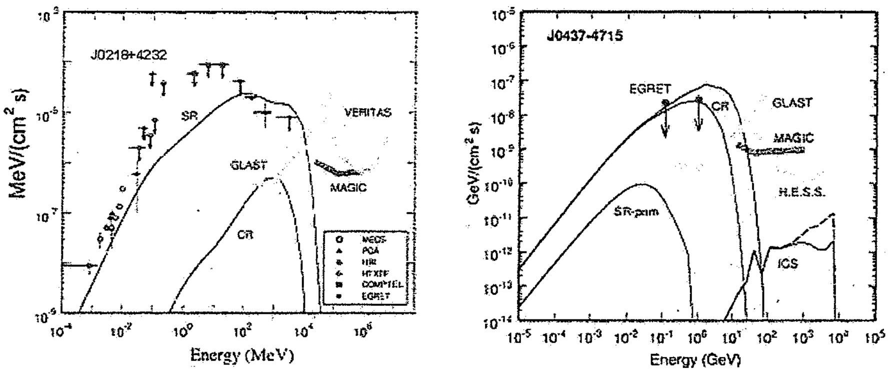

Fig. 23. Predictions of a modified polar cap model for two ms pulsars [62].

els, there are testable predictions for gamma-ray emission from this class of objects. GLAST LAT observations will clearly be able to distinguish among the existing predictions and provide extensive data for ongoing theoretical modeling.

Other population studies, e.g. [63], [64], [65], [26], [62], [66], have used a variety of analyses of gamma-ray pulsar data and models to make predictions of which unidentified EGRET sources will be found to be pulsars and how many pulsars of various types will be seen by GLAST LAT. All agree that LAT should greatly expand the known gamma-ray pulsar population.

One significant feature of the pulsar studies with LAT will be the ability to find pulsed emission without pre-knowledge of a pulsar period from radio or X-ray detections. Only the very brightest pulsars could have been found in a blind search of the EGRET data (e.g. [62], [68]). The much higher sensitivity of the LAT should allow searches for pulsations in most of the bright unidentified EGRET sources [69]. Geminga is unlikely to be the only radio-quiet gamma-ray pulsar.

Another important aspect of GLAST LAT's increased sensitivity will be the ability to measure phase-resolved spectra for the brighter pulsars. Spectral evolution with phase is an important feature in helping resolve differences among models [70], [71], [46]. Figures 24 and 25 show two examples of calculated phase-resolved spectra compared to EGRET data. Although these are among the brightest gamma-ray sources, the spectra for phase regions away from the two main peaks in the light curve are highly uncertain in the data, with significant scatter and large statistical error bars. With 25-30 times the statistics for these and other bright pulsars, LAT will be able to produce similar plots with much better defined phase-resolved spectra (error bars typically 5 times smaller those seen here).

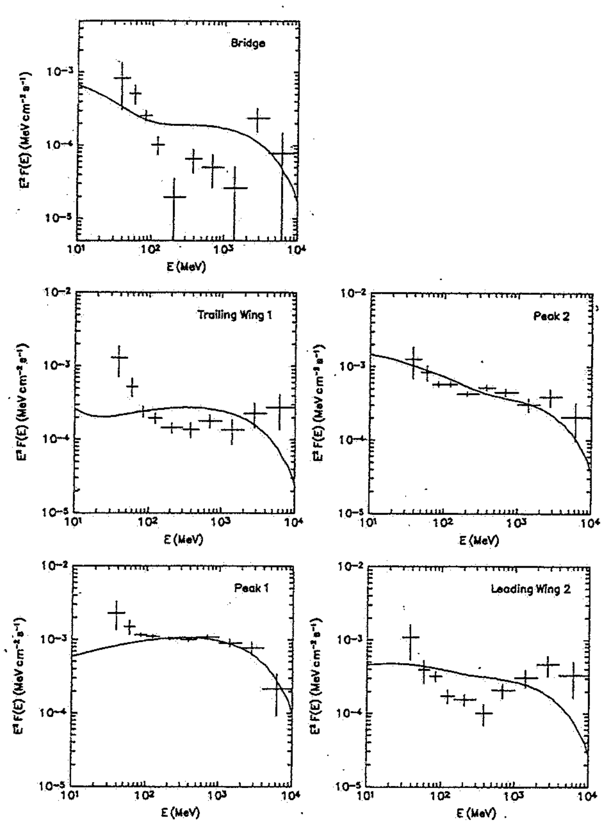

Fig. 24. Comparision of calculated and measured phase-resolved spectra for the Crab pulsar in an outer gap model[70]. With is broader energy range and higher statistics, the LAT data for such spectra will have uncertainties about 5 times smaller than these EGRET points.

Neutron Star Science with GLAST - Pulsar Wind Nebulae

Off-pulse gamma-ray emission from the Crab has been identified as the pulsar wind nebula (PWN) [12], and X-ray plus radio studies suggested other PWN associated with some EGRET sources [72]. The H.E.S.S. detections of PWN such as the "Kookaburra" [49] at TeV energies emphasize that these winds are powerful particle accelerators and gamma-ray sources.

The GLAST LAT will not have spatial resolving power as good as the TeV telescopes for extended sources, but it provides capabilities that complement those of the higher-energy telescopes. Fig. 26 is adapted from [49] to show some of the ways LAT can help resolve the astrophysics of a complex region like this:

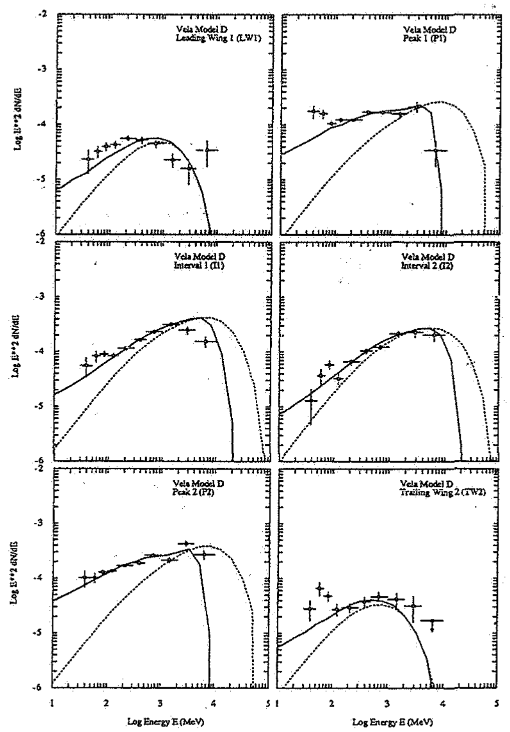

Fig. 25. Comparision of calculated and phase-resolved spectra measured by EGRET for the Vela pulsar in a polar cap model[71]. LAT data will have much better statistics and smaller error bars.

- At GeV energies, a large fraction of the gamma-ray emission may come from PSR J1420−6048, the young pulsar that presumably powers at least part of this PWN. The LAT data can be folded at the known radio pulsar period to determine the characteristics of the pulsed emission. If it is similar to the other gamma-ray pulsars, this pulsed emission will have a high-energy cutoff that can be measured by the LAT.
- This region does contain an unidentified EGRET source, whose 95% confidence position contours are shown. If that source is a point source (such as the pulsar), the LAT will be able to determine its location to better than one arcmin. This positioning could help isolate the source of the radiation.
- By using its higher-energy photons, LAT will be able to resolve the emission to search for the second H.E.S.S. source and investigate its characteristics.
- The LAT will provide broad-band spectral measurements that can be used in combination with multiwavelength observations to model the emission

from the region. If one or more pulsars are seen, off-pulse emission could provide an estimate of the PWN contribution at LAT energies.

As for the case of pulsars, the GLAST LAT PWN studies will be most relevant in a multiwavelength context. At the outset, the LAT observations will focus on discovery of details only suggested by EGRET.

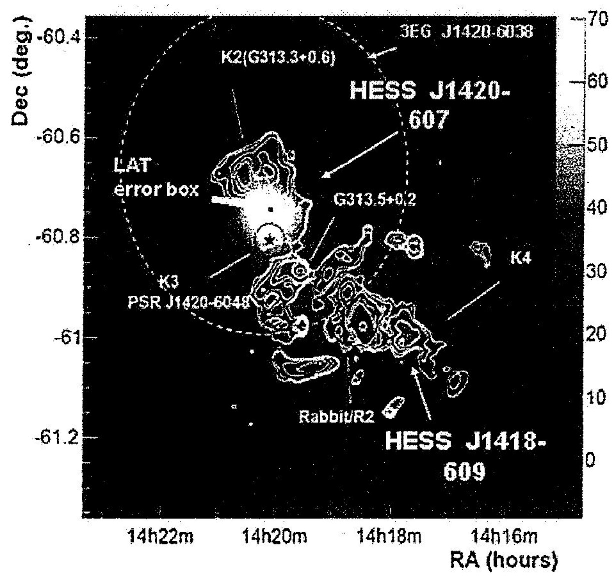

Fig. 26. Observations of the "Kookaburra" region, adapted from [49]. The dashed circle represents the 95% confidence size of the unidentified EGRET source error box. The small black dot in the middle represents the LAT 95% confidence region for a localized source of the same intensity.

5 Summary

Astrophysics is entering a time when gamma-ray observatories will be well positioned to make significant scientific contributions to studies of neutron star systems. As H.E.S.S. has already demonstrated, there will likely be unexpected discoveries. The breadth and depth of new gamma-ray observing capabilities offer many opportunities. To summarize:

- Past results from the Compton Gamma Ray Observatory on pulsars and emerging results from TeV telescopes like H.E.S.S. on pulsar wind nebulae provide a strong incentive to pursue gamma-ray observations of neutron stars and their environments.

- Expansions and improvements in the TeV telescope arrays will enhance their sensitivity and push energy thresholds down.
- AGILE will carry out some important follow-up studies for pulsars suggested but not confirmed by EGRET.
- GLAST has all-sky, high-sensitivity capabilities and plans for cooperative, multiwavelength observations of neutron stars and their surroundings.

References

1. L. M. Bartlett: High Resolution Gamma-Ray Spectroscopy of the Crab. PhD Thesis, University of Maryland, College Park, MD (1994)
2. K. M. V. Apparao: Ap. & Sp. Sc. **25**, 3 (1973)
3. P. L. Marsden: ApJ **278**, L29 (1984)
4. E. P. Ney, W. A. Stein: ApJ **152**, L21 (1968)
5. E. E. Becklin, D. E. Kleinmann: ApJ **152**, L25 (1968)
6. G. L. Grasdalen: PASP **91**, 436 (1979)
7. J. D. Scargle: ApJ **156**, 401 (1969)
8. C.-C. Wu: ApJ **245**, 581 (1981)
9. M. G. Kirsch et al.: Proc. SPIE **5898**, 22 (1984)
10. S. H. Pravdo, P. J. Serlemitsos: ApJ **246**, 484 (1981)
11. G. V. Jung: ApJ **338**, 972 (1989)
12. O. C. deJager et al.: ApJ **457**, 253 (1996)
13. F. Aharonian: ApJ **614**, 897 (2004)
14. B. J. Rickett, J. H. Seiradakis: ApJ **256**, 612 (1982)
15. J. M. Rankin, R. R. Payne, D. B. Campbell: ApJ **193**, L71 (1974)
16. R. N. Manchester: ApJ **163**, L61 (1971)
17. J. Middleditch, C. Pennypacker, M. S. Burns: ApJ **273**, 261 (1983)
18. J. B. Oke: ApJ **156**, L49 (1969)
19. J. W. Percival et al.: ApJ **407**, 276 (1993)
20. F. R. Harnden, Jr., F. D. Seward: ApJ **283**, 279 (1984)
21. F. K. Knight: ApJ **260**, 538 (1982)
22. M. P. Ulmer et al: ApJ **448**, 356 (1995)
23. M. de Naurois et al: ApJ **556**, 343 (2002)
24. T. C. Weekes et al: ApJ **342**, 379 (1989)
25. M. Mori: International Workshop on Energy Budget in the High Energy Universe, February 22-24, 2006, Kashiwa campus of the University of Tokyo, (2006)
26. D. J. Thompson: Gamma ray pulsars. In: *Cosmic Gamma-Ray Sources*, ed by K.S.Cheng, G. E. Romero (Kluwer, Dordrecht Boston London 2004) pp 149–168
27. W. Hofmann: Proc. ICRC 2001, 2785 (2001)
28. W. Hofmann: ICRC 2005, 2785 (2005)
29. F. Aharonian et al.: A&A **435**, L17 (2005)
30. F. Aharonian et al.: A&A **442**, 1 (2005)
31. F. Aharonian et al.: Science **309**, 746 (2005)
32. P. Vincent: Proc ICRC 2005 **5**, 163 (2005)
33. F. Aharonian et al.: A&A **435**, L17 (2005)
34. D. Ferenc: NIM A **553**, 274 (2005)
35. J. Albert et al.: Science **312**, 1771 (2006)

36. J. Holder: Astropart. Phys., in press (2006)
37. J. Holder: Talk presented at Univ. of Delaware (2006)
38. T. Weekes: Astropart. Phys. **17**, 221 (2002)
39. R. Atkins et al: Phys. Rev. Lett. **95**, 251103 (2005)
40. G. Sinnis: Proc ICRC 2005 **5**, 435 (2005)
41. A. Aloisio: Il Nuovo Cimento **24**, 739 (2001)
42. Z. Cao: Proc ICRC 2005 **5**, 101 (2005)
43. F. Schmidt: Workshop on Pulsars, Pulsar-Wind Nebulae, and Supernova Remnants Berlin, April 78 (2005)
44. D. J. Thompson, D. L. Bertsch, R. H. O'Neal, Jr.: ApJ **157**, 324 (2005)
45. H. I. Nel et al.: ApJ **418**, 836 (1993)
46. R. W. Romani: ApJ **470**, 469 (1996)
47. K. Hirotani, A. K. Harding, S. Shibata: ApJ **591**, 334 (2003)
48. F. Aharonian et al.: Science **307**, 1938 (2005)
49. F. Aharonian et al.: A & A in press (2006)
50. M. Tavani et al.: SPIE Proceedings, in press (2006)
51. M. Kramer et al.: MNRAS **342**, 1299 (2003)
52. J. Halpern et al.: ApJ **552**, L125 (2001)
53. D. J. Thompson, S. W. Digel, P. L. Nolan, O Reimer: High-Energy Gamma Rays from Neutron Stars in Supernova Remnants: From EGRET to GLAST In: *Neutron Stars in Supernova Remnants*, Ed. P. O. Slane and B. M. Gaensler. (ASP, San Francisco 2002) pp.65–68
54. A. von Kienlin et al.: SPIE Proceedings, **5488**, 763 (2004)
55. P. Michelson: Instrument for the Gamma-ray Large Area Space Telescope (GLAST) Mission In: *X-Ray and Gamma-Ray Telescopes and Instruments for Astronomy*, Ed. J. E. Trümper, H. D. Tananbaum (SPIE Vol. 4851, 2003) pp. 1144-1150
56. B. Zhang, A. K. Harding: ApJ **532**, 1150 (2000)
57. L. Kuiper et al: A & A **359**, 615 (2000)
58. D. J. Thompson: Adv. Sp. Res. **25**, 659 (2000)
59. J. M. Fierro et al.: ApJ **447**, 807 (1995)
60. T. Bulik, B. Rudak, J. Dyks: MNRAS **317**, 97 (2000)
61. L. Zhang, K. S. Cheng: A & A **398**, 639 (2000)
62. A. K. Harding, V. V. Usov, A. G. Muslimov: ApJ **622**, 531 (2005)
63. I.-A. Yadigaroglu, R. W. Romani: ApJ **476**, 347 (1997)
64. L. Zhang, Y. J. Zhang, K. S. Cheng: A & A **357**, 957 (2000)
65. M. A. McLaughlin, J. M. Cordes: ApJ **538**, 818 (2000)
66. P. L. Gonthier et al.: Ap&SS **297**, 71 (2005)
67. K. T. S. Brazier, G. Kanbach: A & AS **120**, 85 (1996)
68. A. M. Chandler et al.: ApJ **556**, 59 (2001)
69. J. R. Mattox: private communication (2000)
70. K. S. Cheng: Theory of gamma-ray emission from pulsars. In: *Cosmic Gamma-Ray Sources*, ed by K.S.Cheng, G. E. Romero (Kluwer, Dordrecht Boston London 2004) pp 169–203
71. J. K. Daugherty, A. K. Harding: ApJ **458**, 278 (1996)
72. M. S. E. Roberts, R. Romani, N. Kawai: ApJS **133**, 451 (2002)