A Southern Sky Survey with *Fermi* LAT and ASKAP

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We present the prospects for a future joint gamma-ray and radio survey of southern hemisphere sources using the *Fermi* Large Area Telescope (LAT) and the upcoming Australian Square Kilometre Array Pathfinder (ASKAP) radio telescope. ASKAP is a next generation radio telescope designed to perform surveys at GHz frequencies at a much higher survey speed than previous radio telescopes, and is scheduled to start engineering observations in 2011. The survey capabilities of both *Fermi* LAT and ASKAP are described, and the planned science surveys for ASKAP are summarized. We give some expected details of the Variable and Slow Transient (VAST) survey using ASKAP, which will search for transients on timescales from 5 seconds to years. Some observational properties of faint and transient sources seen at gamma-ray and radio wavelengths are summarized, and prospects and strategies for using ASKAP survey data for LAT source counterpart identification are summarized.

I. THE LARGE AREA TELESCOPE

The Large Area Telescope (LAT, Figure 1, [1]) on *Fermi* is a pair-conversion telescope, having a 4x4 grid of detectors (TKR+CAL) surrounded by an ACD. TKRs measure photon direction, CALs measure photon energy. The ACD vetoes charged particle background events. The major elements of the LAT are:

- Tracker (TKR): Stacked Si-strip detector layers with superb position resolution and efficiency, with low-power readout. Multiple tungsten foils allow good angular resolution while providing high conversion efficiency. 1.5 X_0 total depth.
- Calorimeter (CAL): Hodoscopic array of CsI crystals with PIN-diode readout. Segmentation provides shower imaging for improved energy reconstruction and background rejection. Radiation length: 8.4 X_0 total at normal incidence.
- Anti-Coincidence Detector (ACD): Plastic scintillator array for high efficiency charged-particle detection and minimal self-veto of gamma-rays.
- Electronics, DAQ,Trigger: Process and filter events from the LAT. Perform on-board searches for gamma-ray bursts.

The main performance specifications of the LAT are summarized in Table I.

TABLE I. LAT Performance Summary

Energy Range (GeV)	0.02 to > 300
Effective Area (on-axis, > 1 GeV)	8000 cm^2
Angular Resolution (@ 10 GeV)	0.1°
Energy Resolution (on-axis, > 0.1 GeV)	< 15%
Event Absolute Timing	< 10μs
Field of View	2.4 sr
Deadtime per Event	27μs

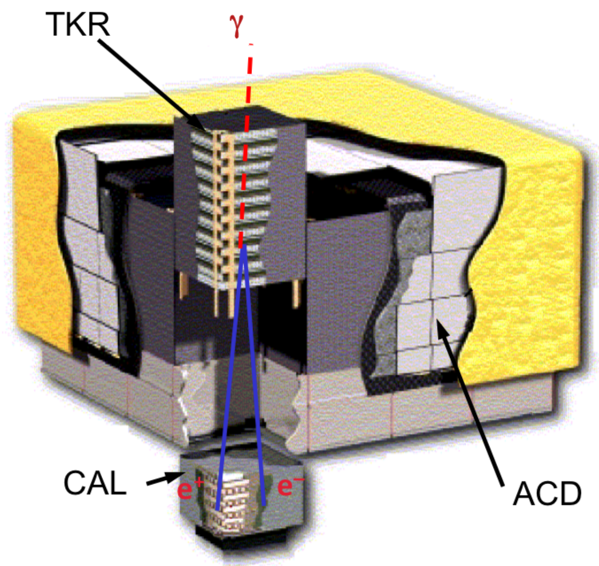

FIG. 1. Cutaway diagram of the LAT showing the ACD, Tracker and Calorimeter. The LAT dimensions are approximately 1.8m x 1.8m x 0.75m.

II. THE LAT SKY SURVEY

The field of view of the LAT covers ~20% of the sky at any instant, and up to 75% of the sky every orbit. In scanning mode the entire sky is observed every 2 orbits (~3 hours). Figure 2 shows the LAT sensitivity to point sources across the sky (in galactic coordinates) for integration periods of 100 seconds, 2 orbits (~192 minutes), 1 day and 1 year. The LAT has less sensitivity on the galactic plane because of the higher diffuse emission there.

The source localization capability of the LAT is shown in Figure 3, which plots the 95% confidence radius for source positions as a function of the source Test Statistic (measurement significance), from the bright source list measured in the first three months

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Work supported in part by US Department of Energy contract DE-AC02-76SF00515.

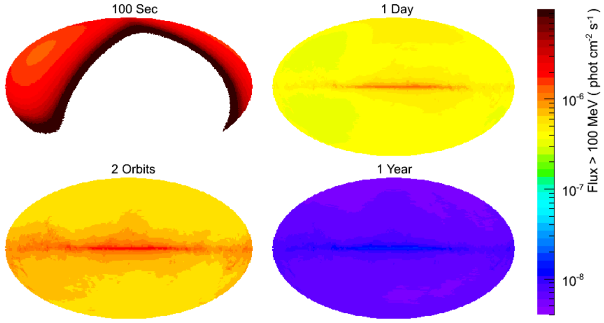

FIG. 2. Sky Coverage and Sensitivity of the LAT Sky Survey on timescales of 100 seconds, 2 orbits, 1 day and 1 year.

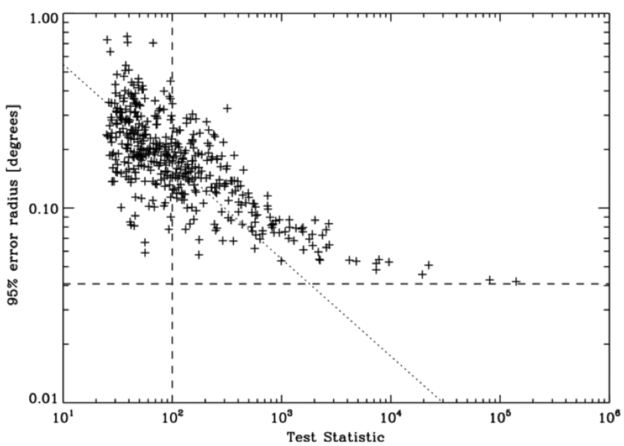

FIG. 3. LAT source position uncertainty, the 95% confidence radius on measured source positions, as a function of the LAT source measurement Test Statistic, for bright sources detected in the first 3 months of the LAT sky survey [2].

of LAT survey data [2]. The brightest sources have a position uncertainty near 0.04, limited by systematic uncertainties, while fainter sources can have a position uncertainty of tens of arc-minutes. Figure 4 shows the distribution of sources in the 3-month bright source list, showing variable and non-variable sources. Measuring correlated variability at other wavelengths is one approach to counterpart identification of LAT sources.

III. ASKAP

Australia and South Africa are the two candidate sites for the future Square Kilometre Array (SKA) radio telescope, the next generation successor to the current largest radio interferometer array telescopes. Final site selection for the SKA is planned for 2012, and demonstrator radio telescopes are currently being constructed at each candidate site. The ASKAP

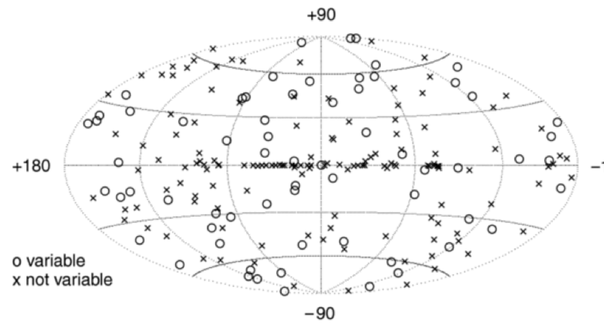

FIG. 4. The positions in Galactic coordinates of the bright sources detected in the first 3 months of the LAT sky survey [2].

(Australian Square Kilometre Array Pathfinder) radio telescope is being developed under the guidance of the ASKAP International Collaboration, led by the Australia Telescope National Facility (ATNF) in Australia [3]. The member institutions of the ASKAP International Collaboration are

- Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia
  - ⋆ Australia Telescope National Facility (ATNF)
  - ⋆ Information and Communication Technologies Centre
- University of Western Australia
- Herzberg Institute of Astrophysics (Canada)
- ASTRON (Netherlands)
- Max Planck Institute (Germany)
- Auckland University of Technology (New Zealand)

ASKAP will be located at the candidate site for the SKA central array in Murchison, Western Australia, (Figure 5) and will be co-located with the Murchison Wide Field Array (MWA), a low-frequency (80-300 MHz) dipole array. The first ASKAP antenna will be on site in late 2009. ASKAP will start partial-array observations in 2011, and full-array observations are scheduled to start in late 2012. At least 75% of ASKAP observing time will be used for several large Survey Science Projects during the first 5 years of operation: 2012 2017.

IV. ASKAP ARRAY CONFIGURATION

The key performance parameters of the ASKAP telescope array are given in Table II. The layout of the ASKAP dishes in the array is shown in Figure 6,

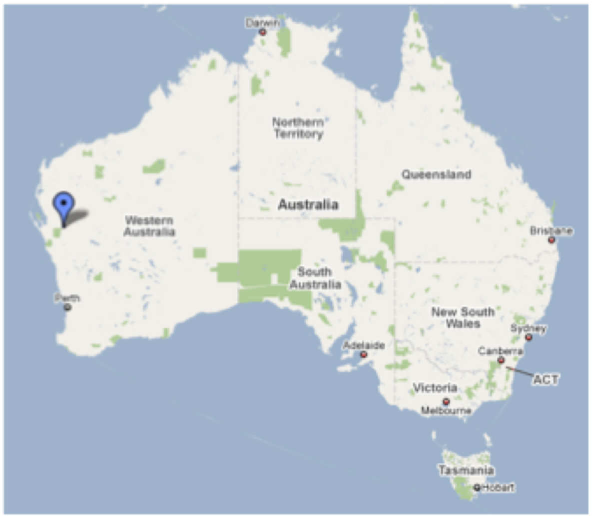

FIG. 5. The site of the ASKAP telescope array center, in Western Australia. The array will be centered at Latitude = 26.7° S, Longitude = 115.5° E.

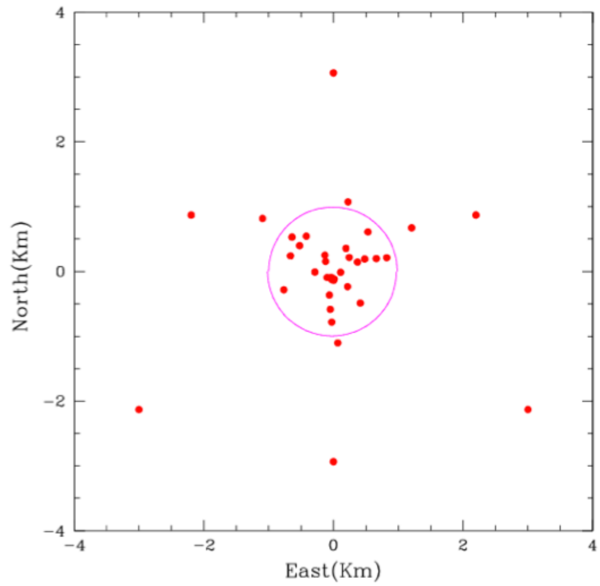

FIG. 6. The ASKAP telescope array layout.

TABLE II. ASKAP Performance Summary [3]

Number of dishes	36
Dish Diameter (m)	12
Dish Area (m^2)	113
Total Collecting Area (m^2)	4072
Aperture Efficiency	0.8
System Temperature	50
Field of View (deg^2)	30
Frequency Range (MHz)	700 - 1800
Bandwidth (MHz)	300
Maximum Channels	16384
Maximum Baseline (km)	6

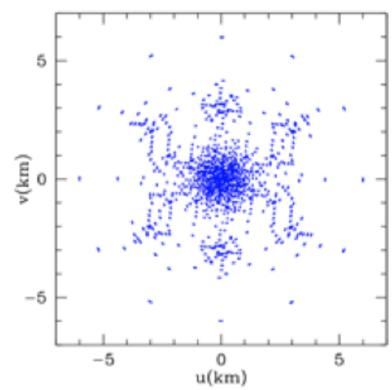

FIG. 7. The *uv* visibility distribution from the ASKAP telescope array for a 12 minute observation of a source at declination −30°.

and examples of the *uv* visibility coverage of the array for a source at declination −30° are shown in Figure 7 for a 12 minute observation, and in Figure 8 for a 10 hour observation.

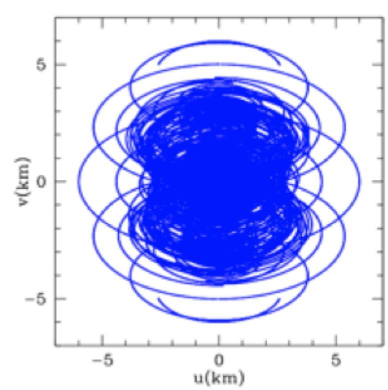

FIG. 8. The *uv* visibility distribution from the ASKAP telescope array for a 10 hour observation of a source at declination −30°.

V. ASKAP SURVEY CAPABILITIES

By using wide-field-of-view phased array feeds to produce a large instantaneous field of view, ASKAP will be able to survey the whole sky vastly faster than is possible with the current generation of radio telescopes. Table III summarizes the capabilities of the ASKAP array in sky survey speed for continuum, spectral line and surface brightness measurements, as a function of angular resolution. Similarly, Table IV summarizes the 1σ sensitivity for 1 hour integrations in continuum, spectral line and surface brightness measurements.

TABLE III. ASKAP Survey Speed Capabilities (deg^2/hour)

Angular Resolution (arcsec)	**10**	**18**	**30**	**90**	**180**
Continuum Survey Speed (300 MHz, 100 μJy)	220	361	267	54	17
Line survey Speed (100 kHz, 5 mJy)	184	301	223	45	14
Surface Brightness Survey Speed (5 kHz, 1°K)	–	–	1.1	18	94

TABLE IV. ASKAP Survey Sensitivity (1 hour observation, 1σ)

Angular Resolution (arcsec)	**10**	**18**	**30**	**90**	**180**
Continuum Survey Sensitivity (300 MHz) (μJy/beam)	37	29	34	74	132
Line survey Sensitivity (100 kHz) (mJy/beam)	2.1	1.6	1.9	4.1	7.3
Surface Brightness Survey Sensitivity (5 kHz) (°K)	51	12	5.2	1.3	0.56

VI. THE VARIABLE AND SLOW TRANSIENT SURVEY

Following a request for science survey proposals starting in 2008, 10 proposals were selected in September 2009 to be performed in the first 5 years of ASKAP operation:

- EMU: Evolutionary Map of the Universe (PI: Norris)
- WALLABY: Widefield ASKAP L-Band Legacy All-Sky Blind Survey (PIs: Koribalski and Staveley-Smith)
- ASKAP-FLASH: The First Large Absorption Survey in H I (PI: Sadler)
- VAST: An ASKAP Survey for Variables and Slow Transients (PIs: Murphy and Chatterjee
- GASKAP: The Galactic ASKAP Spectral Line Survey (PI: Dickey)
- POSSUM: Polarization Sky Survey of the Universe's Magnetism (PIs: Gaensler, Taylor and Landecker)
- CRAFT: The Commensal Real-time ASKAP Fast Transients survey (PIs: Dodson and Macquart
- DINGO: Deep Investigations of Neutral Gas Origins (PI: Meyer)
- The High Resolution Components of ASKAP: Meeting the Long Baseline Specifications for the SKA (PI: Tingay)
- COAST: Compact Objects with ASKAP: Surveys and Timing (PI: Stairs)

The Variable and Slow Transient (VAST) survey is particularly relevant to identification of transient sources detected with Fermi LAT, since it concentrates on the detection and measurement of variable and transient radio sources on timescales down to 5 seconds. The VAST proposal included 3 sub-surveys:

- VAST-Wide: 10,000 square degrees observed every day for 2 years (rms sensitivity = 0.5 mJy/beam).
- VAST-Deep: 10,000 square degrees (rms sensitivity = 0.05 mJy/beam). Fields revisited 8 times at irregularly spaced intervals.
- VAST-GP: 750 square degrees along the Galactic plane plus LMC and SMC (rms sensitivity = 0.1 mJy/beam) repeated weekly for 1 year.

The VAST survey will be complementary to other ASKAP surveys: e.g. the EMU survey has a large single epoch deep survey (rms sensitivity 10 μJy/beam). The VAST proposal also included commensal transient searches in other ASKAP survey data. Since the 10 accepted surveys exceed the 75% goal for ASKAP dedicated survey time, some descope or merging of the VAST surveys may be negotiated. The VAST daily radio survey of much of the southern hemisphere sky will greatly benefit the identification and study of faint and/or variable sources detected by the Fermi LAT. The Fermi mission will end its first 5 years of operation in 2013, with the expected additional five years for the 10-year Fermi mission overlapping well with the ASKAP surveys.

VII. RADIO AND GAMMA-RAY SOURCE PROPERTIES

The bright source list from the first 3 months of the Fermi LAT sky survey contained 205 sources and included 66 sources showing significant variability on weekly or longer timescales. 37 of the 205 bright sources (18%) had no known obvious counterpart at other wavelengths, with most of the unassociated sources being on or near the galactic plane. As the Fermi survey continues and fainter sources are detected, the problem of source identification will worsen: approximately 50% of the sources in the preliminary LAT first year source catalog have no association at other wavelengths (preliminary result). Deep, large area radio surveys can provide many additional source associations. However, current deep surveys (e.g. [4], Figure 9) show that the sky surface density of 1mJy or brighter sources at 1.4 GHz will potentially result in several candidate counterparts per faint LAT source.

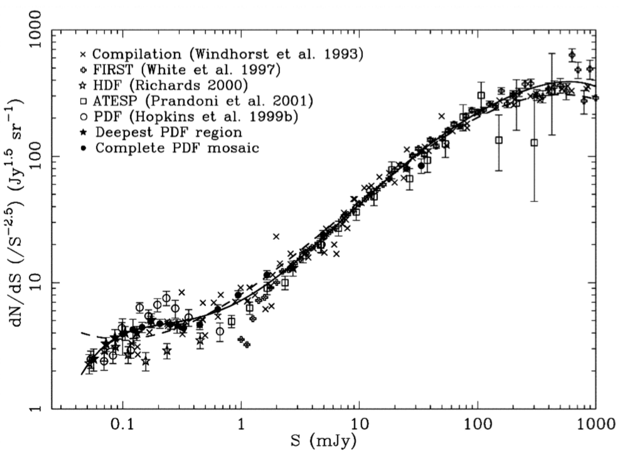

FIG. 9. 1.4 GHz differential radio source counts, from multiple catalogs (from [4]).

Simple correlations of gamma-ray to radio fluxes or luminosities will not provide adequate counterpart identifications. Figure 10 shows the scatter in the correlation of gamma-ray flux to radio flux for sources in the LAT bright AGN source list [2]. Additionally correlating source variability data from the LAT and VAST surveys, for both galactic and extragalactic sources will aid radio counterpart identification to LAT sources, and will also aid in separating foreground radio variability effects such as scintillation from intrinsic source variations. We expect to apply both spatial and temporal analysis to LAT and ASKAP data for finding LAT source counterparts, and for their further study. Daily radio measurements from VAST should generally provide sufficient time sampling for correlation to gamma-ray source variability observed with the LAT.

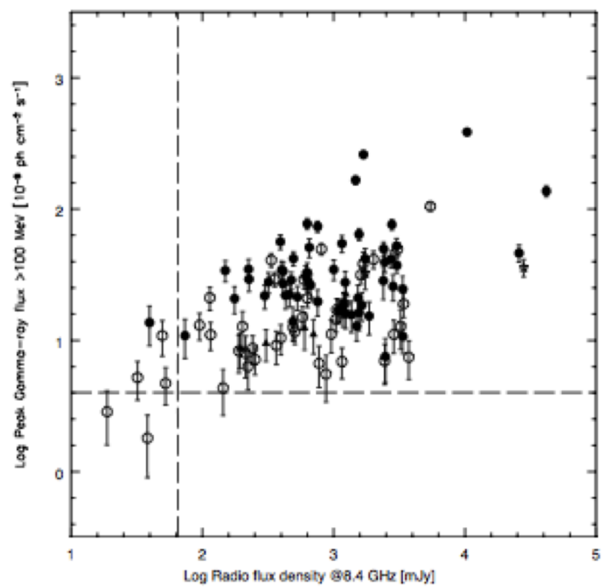

FIG. 10. Gamma-ray to radio source flux correlation for Flat Spectrum Radio Quasars (filled circles) and BL Lacs (open circles), for the LAT bright AGN source list [5].

ACKNOWLEDGMENTS

This work is supported by Stanford University and the SLAC National Accelerator Laboratory under DOE contract DE-AC03-76SFO0515 and NASA grant NAS5-00147. Non-US sources of funding also support the efforts of *Fermi* LAT collaborators in France, Italy, Japan and Sweden.

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