An All-Sky Search for Intermediate-Scale Structure Using Milagro

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Abstract: Milagro is a TeV gamma-ray observatory with a $\sim$ 2 sr field of view and a $> 90\%$ duty factor. The large field of view and long observation time make Milagro ideal for surveying large regions of the Northern Hemisphere sky. A previous all-sky survey searched for point sources [4], but the analysis is easily adaptable to look for intermediate-scale sources ($\sim 10^\circ$) as well. A search on intermediate scales has been conducted, and 2 regions are seen with a statistical significance above 11σ. Analysis to determine the nature of these regions is underway.

The Milagro Detector

Milagro [4] is a water-Cherenkov detector at an altitude of 2650m capable of continuously monitoring the overhead sky. It is composed of a central 60m x 80m pond with a sparse 200m x 200m array of 175 "outrigger" tanks surrounding it. The pond is instrumented with two layers of photomultiplier tubes. The top "air-shower" layer consists of 450 PMTs under 1.4m of purified water, while the bottom "muon" layer has 273 PMTs located 6m below the surface. The air-shower layer allows the accurate measurement of shower particle arrival times used for direction reconstruction and triggering. The greater depth of the muon layer is used to detect penetrating muons and hadrons to help distinguish between gamma-ray- and hadron-induced air showers. The outrigger array improves the angular resolution of the detector by providing a more accurate core location and a longer lever arm with which to reconstruct the events.

Milagro's large field of view ($\sim$ 2sr) and high duty cycle ($> 90\%$) allow it to scan the entire overhead sky continuously, making it well-suited for searching for new sources of TeV gamma rays, as well as monitoring known sources at higher energies. Previous surveys [4, 2] were optimized for sources smaller than Milagro's $\sim 1.1^\circ$ angular resolution. However, the analysis can easily be modified to search for larger sources.

Analysis Method

In the analysis, a signal map is made based on the arrival direction of each event. A background map is also created using a technique called "direct integration" [4], in which a two-hour time interval is used to generate the background. The accuracy of the background map depends on the assumption that the shape of the local cosmic ray flux is constant during the two hours. Since this time interval corresponds to the earth rotating 30°, this analysis is relatively insensitive to features with an extent larger than $\sim 30^\circ$ in Right Ascension.

In the standard analysis, the signal and background maps are smoothed with a bin size that is optimal for Milagro's angular resolution (PSF smoothing may be used instead), and then the maps are compared. In this analysis, however, a square bin of size 10.1° in Declination and $10.1^\circ/cos(\delta)$ in Right Ascension is used to increase the sensitivity to larger features. Because a 2-hour (30° in R.A.) background generation interval is used, a bin size larger than 10° is not feasible, especially at higher declinations. The analysis was applied to 6.5 years of data, beginning in July 2000 and ending in January 2007.

Preliminary Results

The top half of Figure 1 shows a preliminary all-sky map generated using $10.1°$ binning with no gamma/hadron cut applied. The bottom map was optimized for gamma-ray point sources and is included for comparison. While the Crab Nebula (at RA $= 83.6°$, Dec $= 22.0°$) is seen at 15σ in the bottom map, the significance at the Crab's location is only 4.7σ in the top map. This decrease is due to the large bin size as well as the lack of a gamma/hadron cut. The Cygnus Region (at RA $\approx 305°$, Dec $\approx 40°$), which was discussed in [1], is clearly visible in both maps. The regions of excess in the top map at RA $\approx 70°$, Dec $\approx 15°$ and at RA $\approx 125°$ both have peak significances above 11σ (above 9.5σ after accounting for the trials of searching the map) and are clearly not due to statistical fluctuations. They are visible in maps with gamma/hadron cuts as well, though not as clearly. Systematic effects such as seasonal variation and year-to-year detector variation have been excluded as possible causes. In addition, the possibility of an underestimation of the background in these regions has been considered, but these features are found to be due to an excess in the signal map.

Note that these two regions are paralleled by regions of deep deficit. This is because the background estimate has been contaminated (raised) by the large excesses. The effect of each excess extends out to $\pm 30°$ in RA because of the 2-hour background generation interval.

Discussion

The region at RA $\approx 70°$, Dec $\approx 15°$ is similar to an excess seen in results published by the Tibet ASγ Collaboration [3], which they labelled the "tail-in" anisotropy, and it is coincident with the direction opposite to the relative motion of the solar system with respect to the neutral gas [6]. The excess at RA $\approx 125°$ is not readily visible in the Tibet results. It is also noteworthy that this analysis is not suitable for features broader than $\sim 30°$, such as the deficit in the Tibet maps. This deficit is also seen by Milagro, but with a different analysis [5].

The source of these features is not clear. Diagnostics, which rely on Milagro's ability to differentiate between gamma rays and hadrons, are underway to determine whether the excess is due to gamma rays or cosmic rays. These results will be presented at the conference and included in the final version of this paper.

References

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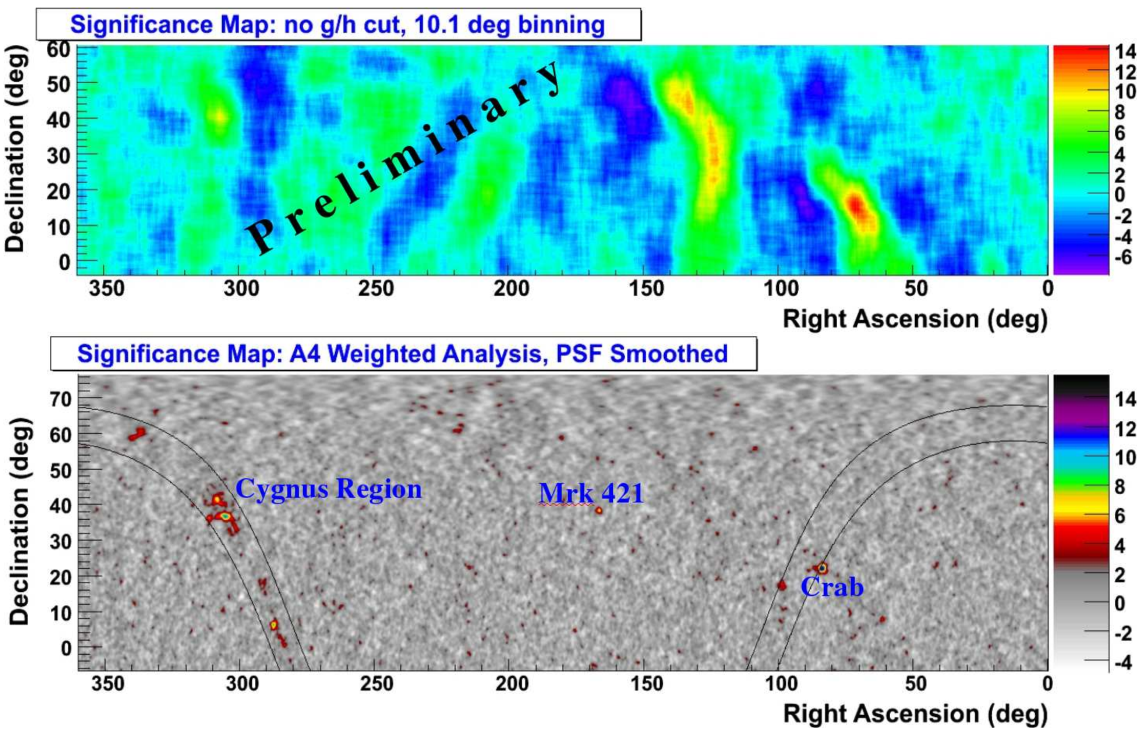

Figure 1: The top map is a preliminary all-sky significance map made with $10.1°$ binning and no gamma/hadron cut. The map is cut off above Dec$= 60°$ because the width of the signal bin begins to approach the two-hour width ($30°$) of the background generation interval. The bottom map was optimized for gamma-ray point sources and is included for comparison. The black curves outline the Galactic Plane (at $b = \pm 5°$).