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Extragalactic Sources of TeV Gamma Rays: A Summary

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Abstract

The development of techniques whereby gamma rays of energy 100 GeV and above can be studied from the ground, using indirect, but sensitive, techniques has opened up a new area of high energy photon astronomy. The most exciting result that has come from these is the detection of highly variable fluxes of TeV gamma rays from the relativistic jets in nearby AGN. The recent detection of signals from a starburst galaxy and from a radio galaxy opens the possibility that the extragalactic emission of TeV gamma rays is a ubiquitous phenomenon. Here we attempt to summarize the properties of the sources detected so far.

Key words: gamma-ray astronomy; atmospheric Cherenkov radiation; AGN.

1 Introduction

This symposium comes at an interesting time in the history of Very High Energy (VHE) gamma-ray astronomy. The TeV source catalog has now swelled to respectable proportions and is attracting increasing attention amongst theorists and observers at longer wavelengths. The atmospheric Cherenkov imaging technique has been demonstrated to be an effective tool at energies greater than 300 GeV. No other technique has been suggested that is competitive in the energy region from 50 GeV to 50 TeV; clearly, further efforts to improve and extend the technique are justified. In fact a new generation of instruments is under development and the next symposium will surely be dominated by their achievements.

It is 4.5 years since the first symposium on the TeV Astrophysics of Extragalactic Sources was held at the CfA in Cambridge (1). These proceedings show that there has been significant progress since that time. As we discuss below, not only has the number of detected objects increased (and with this the depth of the universe that is probed) but the number of kinds of extragalactic sources has also increased; this is a prediction of good things to come as the sensitivity and range of the telescopes is improved.

Although there has been considerable activity on the theoretical front with the development of models to explain the observed phenomena, there is still no consensus even on such basic things as the nature of the progenitor particles. This is still an observation-driven field and seems likely to be so for some time to come. Clearly the results of multi-wavelength observations are indicative of complex mechanisms and the simple models that have been proposed have a long way to go in providing a full explanation.

Here we will not attempt to give either a summary of the symposium or a comprehensive review of the field. The papers in this volume speak for themselves and describe the progress in the field; recent reviews can be found elsewhere (2); (3); (4); (5). The next generation of instruments: CANGAROO-III, HESS, MAGIC and VERITAS will reach a level of sensitivity such that they are effectively limited by the cosmic electron background; they should all be online by 2004-2006.

2 Status of TeV Gamma-ray Astronomy c. 2003

An updated catalog of sources is shown in Table 1 and is plotted in Figure 1. The criterion for inclusion in this catalog is that the detection should be significant and be published in the refereed literature. Four sources have been added since the last catalog (6). Of more significance perhaps is that three new classes of object are represented (starburst galaxies, radio galaxies, OB Associations). It is noteworthy that many of the sources listed are not in the EGRET Catalog (7), an indication that the TeV sky opens a new window on the universe. The allotted grade gives some measure of the credibility that should be assigned to the reported detections; "A" sources have been independently verified at the 5 σ level. On this scale the EGRET sources would be classified as "B" (except for 3C273 which would be classified as "A" since it was also detected by COS B (8); (9)). In this new catalog the status of several of the TeV sources (marked with an asterisk) has been upgraded (and only one has been downgraded). This suggests that the field has achieved a degree of maturity and that systematic effects in most experiments (but perhaps not all) are understood and accounted for. We propose therefore that an acceptable standard for the publication of a claim for the detection of a new source by a mature experiment should be the 4 σ level of significance.

Table 1
Source Catalog c.2003

TeV Catalog Name	Source	Type	Discovery Date/Group	EGRET 3rd. Cat.	Grade
TeV 0047−2518	NGC 253	Starburst	2003/CANG.	no	B*
TeV 0219+4248	3C66A	Blazar	1998/Crimea	yes	C−
TeV 0535+2200	Crab Nebula	SNR	1989/Whipple	yes	A
TeV 0834−4500	Vela	SNR	1997/CANG.	no	C*
TeV 1121−6037	Cen X-3	Binary	1999/Durham	yes	C
TeV 1104+3813	Mrk 421	Blazar	1992/Whipple	yes	A
TeV 1231+1224	M87	Radio Gal.	2003/HEGRA	no	C
TeV 1429+4240	H1426+428	Blazar	2002/Whipple	no	A*
TeV 1503−4157	SN1006	SNR	1997/CANG.	no	B*
TeV 1654+3946	Mrk 501	Blazar	1995/Whipple	no	A
TeV 1710−4429	PSR 1706−44	SNR	1995/CANG.	no	A
TeV 1712−3932	RXJ1713.7−39	SNR	1999/CANG.	no	B+*
TeV 2000+6509	1ES1959+650	Blazar	1999/TA	no	A*
TeV 2032+4131	CygOB2	OB assoc.	2002/HEGRA	yes†	B
TeV 2159−3014	PKS2155−304	Blazar	1999/Durham	yes	A*
TeV 2203+4217	BL Lacertae	Blazar	2001/Crimea	yes	C*
TeV 2323+5849	Cas A	SNR	1999/HEGRA	no	B*
TeV 2347+5142	1ES2344+514	Blazar	1997/Whipple	no	A*

† CygOB2 lies within the 95% error ellipse of the EGRET source 3EG J0233+4118.

3 Extragalactic TeV Sources

Arguably the most exciting results to come from the search for TeV sources of gamma rays has been the discovery that many of the nearby blazars are detectable sources. This was certainly not anticipated although some of the earliest TeV observations were directed towards radio galaxies (10) and quasars (11). The detection of 3C273 by COS B should perhaps have alerted TeV observers to the possibility that AGN might be denizens of the TeV cosmic zoo. However the spectrum was rather soft and did not suggest that even this, the closest quasar, would be detectable at TeV energies. By and large, the AGN community was equally unexcited by this detection and the discovery

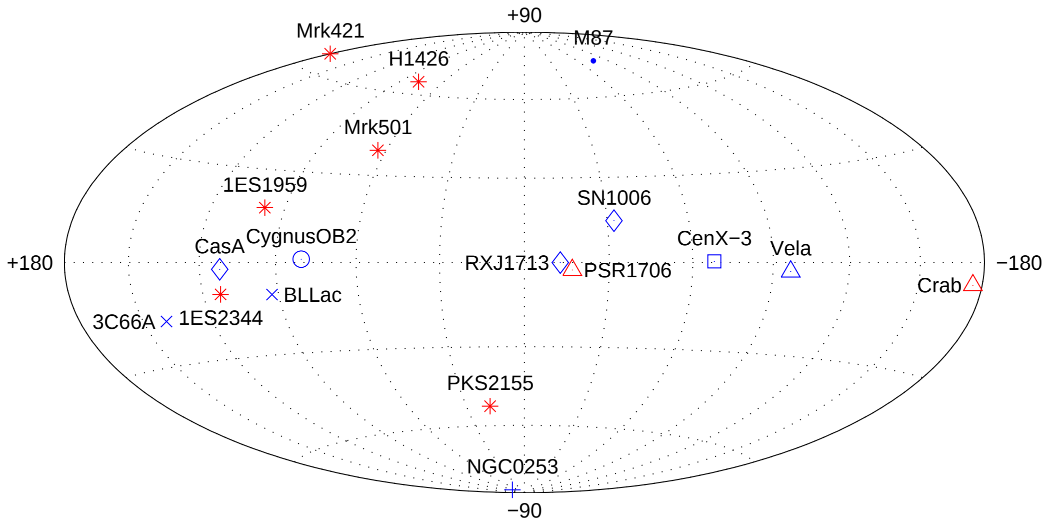

Fig. 1. The 18 claimed sources of TeV gamma rays c. 2003; confirmed sources are drawn in red.

by EGRET that the 100 MeV sky was dominated by blazars came as a real surprise to the larger high energy astrophysics community.

The fact that these EGRET AGN all had flat spectra with little sign of a flattening above 10 GeV was auspicious for TeV astronomy. However no firm predictions were made of the fluxes to be expected and early observations of a selection of these sources by ground-based observers had disappointing results (12). It was not until the detection of Markarian 421 (Mrk 421) (13) that it became apparent that AGN might be an important TeV phenomenon.

By the time AGN had been established as MeV-GeV sources by EGRET, the sensitive atmospheric Cherenkov imaging technique had been developed. Given the high degree of variability now detected in TeV sources it is perhaps fortunate that the first source seen at VHE energies was the Crab Nebula (14), a notoriously steady source. One can only speculate at the controversy that would have ensued if the highly variable Mrk 421 had been the first source reported with the new VHE techniques!

In all, ten extragalactic objects have been reported as sources of VHE gamma rays and their properties are summarized in Table 2. The integral fluxes that were reported in the detection papers (referenced in the second column), are quoted above the peak response energy (E_{peak}) at which they were detected (as given in the last column). Their positions are shown in Table 3. It should be noted that only six of the AGN entries have been independently confirmed at the 5 σ level and hence are classified as A sources. All of the VHE blazars detected to date are relatively close-by with redshifts ranging from 0.031 to 0.129, and perhaps to 0.444; they are all members of the BL Lacertae blazar subclass (BL Lacs). These objects are characterized by few or no emission lines and are labeled Low frequency peaked (LBL) or High frequency peaked (HBL) depending upon the waveband, radio or X-ray, in which their detected synchrotron emission peaks.

Accurate derivation of the VHE spectrum is important for many reasons. Since these are the most energetic photons detected from blazars, the shape of their spectrum is an important input parameter to emission models and can therefore impose severe constraints on them. Multi-wavelength campaigns involving TeV observations which provide information on how the TeV spectrum varies with flux constrain key model input parameters. By comparing such variations to those at longer wavelengths, especially when the observations are simultaneous, much can be inferred about the location and the nature of the progenitor particles. Spectral features, such as breaks or cut-offs, can indicate changes in the primary particle distribution or absorption of the gamma rays via pair-production with low energy photons at the source or in intergalactic space.

The high flux VHE emission from Markarian 501 (Mrk 501) in 1997 (25); (26); (27); (28) and Mrk 421 in 2001 (29); (30); (31) has permitted detailed spectra to be extracted. Measurements are possible over nearly two decades of energy. As many as 25,000 photons were detected in these outbursts so that the spectra were derived with high statistical accuracy. Unlike the HE sources where the photon-limited blazar measurements are consistent with a simple power law, there is definite structure seen in the VHE measurements (27); (32) with evidence for an exponential cut-off in the spectra of some blazars. For Mrk 421, this cut-off is $\approx$ 4 TeV and for Mrk 501 it is $\approx$ 3-6 TeV. The coincidence of these two values suggests a common origin, i.e., a cut-off in the acceleration mechanisms in the blazars or perhaps the effect of the infra-red absorption in extragalactic space. Attenuation of the VHE gamma rays by pair-production with background infra-red photons could produce a cut-off that is approximately exponential. Indeed, consistent with this expectation, the spectrum of the more distant blazar H1426+428 shows evidence for spectral flattening at energies above 1 TeV (33).

Table 2
Extragalactic TeV Sources: Gamma-ray Properties

Source (Det. Paper)		Class	F_γ (mean) > 100 MeV 10^{-8}cm^{-2}s^{-1}	F_γ (Det.) $> E_{peak}$ 10^{-12}cm^{-2}s^{-1}	E_{peak} (Det.) TeV
NGC 253	(15)	Starburst Gal.	U.L.	7.8	0.52
3C66A	(16)	BL Lac(LBL)	18.7	30.0	0.90
Mrk 421	(13)	BL Lac(HBL)	13.9	15.0	0.50
M87	(17)	Radio Galaxy	U.L.	1.0	0.73
H1426+428	(18)	BL Lac(HBL)	U.L.	20.4	0.28
Mrk 501	(19)	BL Lac(HBL)	U.L.	8.1	0.30
1ES1959+650	(20)†	BL Lac(HBL)	U.L.	29.4	0.60
PKS2155−304	(21)	BL Lac(HBL)	13.2	42.0	0.30
BL Lacertae	(22)	BL Lac(LBL)	11.1	21.0	1.00
1ES2344+514	(23)	BL Lac(HBL)	U.L.	11.0	0.35

† No flux was quoted in the initial detection paper (20); the flux from (24) is quoted here.

Table 3
Extragalactic TeV Sources: Position and Size

Source	z	R. A. h/m/s	Declination d/m/s	Gal. Lat. d/m/s	Gal. Long. d/m/s
NGC 253†	0.0006	00 47 06	−25 18 35	94 32 39	−87 56 15
3C66A	0.444	02 19 30	+42 48 30	139 39 42	−17 11 04
Mrk 421	0.031	11 04 27	+38 12 32	179 49 56	+65 01 50
M87††	0.004	12 30 49	+12 23 28	283 46 18	+74 29 26
H1426+428	0.129	14 28 33	+42 40 20	77 29 07	+64 53 53
Mrk 501	0.034	16 53 52	+39 45 36	63 35 59	+38 51 35
1ES1959+650	0.048	19 59 59	+65 08 55	98 00 13	+17 40 10
PKS2155−304	0.117	21 58 52	−30 13 32	17 43 50	−52 14 44
BL Lacertae	0.069	22 02 43	+42 16 40	92 35 20	−10 26 26
1ES2344+514	0.044	23 47 05	+51 42 18	112 53 31	−09 54 28

†The emission from this object has been found to be extended.
††Although the results are compatible with a point-like source, extended emission cannot be excluded.

4 Source Narrative

NGC 253: This is the first starburst galaxy detected and also the closest (2.5 Mpc) source of extragalactic gamma rays. Starburst galaxies are the site of extraordinary supernovae activity and were postulated to be sources of VHE cosmic rays and gamma rays (34). The detection by CANGAROO-II in 2002 was at the 11 σ level (15). It was observed to have a very steep spectral index (-3.75) which implies that most of the signal is close to the telescope threshold. The source was extended with the same elongation as the optical source. A model of the source has been proposed (35). There are many other nearby starburst galaxies (e.g. M82, M81, IC342) so this detection opens up the possibility that there will be many more starburst detections even with the present generation of telescopes.

3C66A: This is, perhaps, the least certain of the TeV detections; it was reported by the Crimean Astrophysical Observatory at the 5.1 σ level of significance (16). Although a well-studied AGN and detected by EGRET, 3C66A seems an unlikely candidate for TeV emission because of its large redshift (z = 0.444) and its classification as an LBL. Upper limits have come from other observations (12); (36) but these were at other epochs and the source could be time variable on long time-scales. It was bright at longer wavelengths during the observations by the Crimean group.

Mrk 421: This was the first AGN detected at TeV energies (13) and it remains the prototype of TeV AGN because its signal strength is, on average, 30% of the Crab (and often much stronger). It is the weakest blazar detected by EGRET in the 3rd Catalog (7) and also the closest.

Whipple observations of Mrk 421 during 1994 revealed the first clear detection of flaring activity in the VHE emission from an AGN. A 10-fold increase in the flux, from an average level that year of approximately 15% of the Crab flux to approximately 150% of the Crab flux was observed. The observations of Mrk 421 in 1995 (37) revealed several distinct episodes of flaring activity as in previous observations; perhaps more importantly though, they indicated that the VHE emission from Mrk 421 was best characterized by a succession of day-scale or shorter flares with a baseline emission level below the sensitivity limit of the Whipple detector.

The VHE emission from Mrk 421 was seen to flare on sub-day time-scales in 1996, with the observations of two short flares (38). In the first flare the flux increased monotonically during the course of ~2 hours of observations. This flux is the highest observed from any VHE source to date. The second flare, observed a week later, although weaker, was remarkable for its very short duration: The entire flare lasted approximately 30 minutes with a doubling and decay time of less than 15 minutes. These two flares exhibited the fastest time-scale variability, by far, seen from any blazar at any gamma-ray energy.

During 2001, Mrk 421 exhibited exceptionally strong and long-lasting flaring activity (39). It was observed extensively with the Whipple telescope during this time and a large database of over 23,000 gamma-ray photons was collected allowing very accurate spectral information to be derived (29). The data are best described by a power law with an exponential cutoff:

$\frac{\mathrm{dN}}{\mathrm{dE}} \propto \mathrm{E}^{-2.14\pm0.03_{\mathrm{stat}}} \exp\left[-\frac{\mathrm{E}}{4.3\pm0.3_{\mathrm{stat}}}\right] \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$ where E is in units of TeV.

The data were binned according to the flux level that Mrk 421 was in when they were recorded and spectra were derived for each flux level. A clear correlation was found to exist between the spectral index and the photon flux and, the spectra were all found to have exponential cutoffs consistent with the average value of 4.3 TeV (31). Spectral measurements of Mrk 421 from previous observing seasons by the Whipple collaboration were also found to be consistent with this flux-spectral index correlation, suggesting this to be a long-term property of the source. The spectral index was found to vary between $1.89 \pm 0.04_{stat} \pm 0.05_{syst}$ in a high flux state and $2.72 \pm 0.11_{stat} \pm 0.05_{syst}$ in a low state.

During its dramatic outburst in 2001, Mrk 421 was also detected by the STACEE detector at energies above 140 GeV (40) and by the CANGAROO-II telescope at energies above 10 TeV (41).

M87: This is one of the brightest nearby radio galaxies and is an obvious potential source of high energy radiation since the jet displays evidence for synchrotron radiation and time variability. The angle of the jet is about 30° (42) which means that it is unlikely to have the same observational gamma-ray properties as the blazars. In fact it was not detected by EGRET and the positive observation by the HEGRA group (17) was a surprise. Although the detection was only at the 4 σ level of significance (weaker than any of the other sources in the TeV catalog) it is a potentially exciting result as it opens up the possibility that many AGN may be observable whose axes are not pointing directly towards us. It is a weak source and its detection required 83 hours of observation. It was not seen in observations at lower energies (43); (44) but the exposures, and hence the flux sensitivities, were limited. The detection of M87 revives interest in the reported detection of Centaurus A in 1975 (45) which, although not confirmed in later, more sensitive, observations, was at a time when the source had an abnormally high microwave flux.

H1426+428: This source is of interest primarily because, at a redshift of 0.129, it is the most distant confirmed source of TeV gamma rays; three different groups have reported significant detections (46); (47); (48). It is weak source (typically 6% of the Crab) and, having its synchrotron peak located at higher frequencies than any of the other TeV blazars, is classified as an “extreme” HBL (49). It was not seen by EGRET. The initial detection by the VERITAS group was at the 5.8 σ level of significance and was based on 44.4 hours of observation. The source is also significant in that it was predicted to be a detectable TeV emitter based on its hard X-ray spectrum (50). The source is definitely variable on time-scales of a year and maybe on times as short as a day. The energy spectrum, which has been derived by three groups, is found to be quite steep. It is well described by a power law with a spectral index between 250 GeV and 1 TeV of 3.50 ± 0.15 derived by the VERITAS Collaboration (51) and of 3.66 ± 0.41 by CAT (48). The HEGRA group derived a spectral index of 2.6 ± 0.6 between 700 GeV 1.4 TeV; above this energy, consistent with the expected signature of absorption of the TeV gamma rays by the extragalactic infra-red photons, evidence for a break in the spectrum was found (33).

Mrk 501: Historically Mrk 501 is important because, when it was detected in 1995 (19), it was the first TeV source to be detected that had not previously been detected by EGRET; hence it established TeV extragalactic astronomy as a discipline in its own right. The properties of Mrk 501 are very similar to those of Mrk 421 although in general the characteristic time-scales seem longer with the flux levels varying less rapidly. In 1997, the VHE emission from Mrk 501 increased dramatically. Fortunately this was a time when several new telescopes were coming on-line so that it was well-observed (52); (53). After being the weakest known source in the VHE sky, in 1995-96 it became the brightest, with an average flux greater than that of the Crab Nebula (whereas previous observations had never revealed a flux >50% of the Crab flux). The amount of day-scale flaring increased and, for the first time, significant hour-scale variations were seen. It was also detected by EGRET for the first time. The Mrk 501 spectrum is similar to that of Mrk 421 and can be represented by:

$$\frac{dN}{dE} \propto E^{-1.92 \pm 0.03_{stat} \pm 0.20_{syst}} \exp\left[-\frac{E}{6.2 \pm 0.4_{stat}{}^{+2.9}_{-1.5}{}_{syst}}\right] m^{-2}\ s^{-1}\ TeV^{-1}$$

(28) where E is in units of TeV.

1ES1959+650: This was first reported in conference proceedings by the Telescope Array group operating in Dugway, Utah (20) in 2000. Upper limits were reported by other groups (54). In 2002, the HEGRA Collaboration reported their detection of 1ES1959+650 (55). The detection was dramatically confirmed later in 2002 when an outburst was seen by several groups (24); (56); (57). Although the quiescent level was only about 5% of the Crab, when it flared its flux was 5 times that of the Crab. Correlations were reported with optical and X-ray observations (58). 1ES1959+650 was not seen by EGRET. The differential energy spectrum has been derived by Aharonian et al.(56) and is well described by a power law with an exponential cut-off during flaring states:

$\frac{dN}{dE} \propto E^{-1.83 \pm 0.15_{stat} \pm 0.08_{syst}} \exp\left[-\frac{E}{4.2^{+1.8}_{-0.6}{}_{stat} \pm 0.9_{syst}}\right] m^{-2}\ s^{-1}\ TeV^{-1}$ where E is in units of TeV.

The low state spectrum is best represented by a pure power law (56) with a spectral index of $3.18 \pm 0.17_{stat} \pm 0.08_{syst}$.

Extensive multiwavelength observations on 1ES1959+650 were carried out during May-July 2002 (59). During this time, a TeV gamma-ray flare was observed which had no counterpart at X-ray energies. This "orphan flare" is difficult to explain in terms of one-zone synchrotron self-Compton (SSC) models. Several possibilities are explored in (60) including multiple-component SSC models, external Compton models and proton models. The latter seems the least likely explanation since the X-ray and gamma-ray flux from 1ES1959+650 were found to be correlated during the rest of the observing campaign.

PKS2155−304: This BL Lac is very bright in the ultraviolet and is classified as a HBL. It is highly variable in X-rays. It is strongly detected by EGRET with a hard spectrum (index -1.71 ± 0.24). It was first reported by the University of Durham group working in Narrabri, Australia (21) who saw a signal at the 6.8σ level of significance. Upper limits were also reported (61); (62). It was dramatically confirmed by the report at this symposium by the HESS group who saw it at the 10.1σ level in just 2.2 hours of observation. This is the first blazar detected in TeV gamma rays in the southern hemisphere.

BL Lacertae:

This is the object after which this class of AGN is named. It is now classified as a LBL like many of the EGRET-detected AGN. The paper (63) that reported the detection of BL Lacertae by EGRET also reported an upper limit at TeV energies from the Whipple group. Subsequently the Crimean group reported the detection of this source at the 7.2 σ level of significance (22). It was optically quite bright at this epoch (July-September, 1998). BL Lac and 3C66A are the only LBLs that have been reported at TeV energies; it is important that these detections at TeV energies be confirmed as they place severe constraints on source models.

1ES2344+514: This AGN was reported by the Whipple group in 1998 (23) as a TeV source based on observations made in 1995. Most of the reported signal came in one night so, if real, the source is highly variable. Indeed, *Beppo*SAX observations of 1ES2344+514 have revealed it to be highly variable at hard X-ray energies (64) with the overall X-ray spectral shape varying with intensity. Its synchrotron peak frequency was seen to shift by a factor of ≈ 30 between observations taken in 1996 and in 1998. This behaviour is typical of HBLs and has, for example, been also observed in Mrk 501 (65). A confirmation of 1ES2344+514 has been reported by the HEGRA group (66) and by the

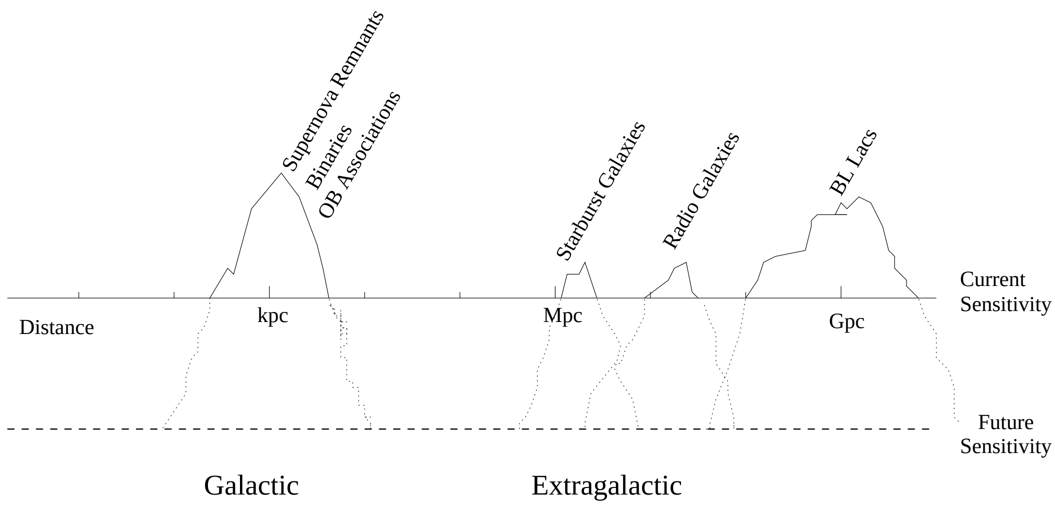

Fig. 2. Tips of the Icebergs in the TeV Universe.

Whipple group (67). No spectrum has been reported. At the peak of its flaring activity it was 60% of the strength of the Crab.

5 Future Prospects

With the next generation of ground-based arrays of telescopes now coming online, it is expected that the number of extragalactic sources detected above 100 GeV will increase tenfold. Spectral measurements will permit detailed models to be confronted with observations. It may be possible to measure the spectral cut-offs between 10 GeV and 100 GeV and to distinguish between those that are intrinsic to the source and those that are due to the extragalactic infra-red background.

The most exciting aspect of the recent results is the diversity of objects that are now proving to be VHE gamma-ray sources. Hopefully each of these detections is only the tip of the iceberg of each class of source (Figure 2) and, as the flux sensitivity improves, the other members of the class will be detectable. It is noteworthy that although the number of sources in the TeV Catalog (Table 1) is still small, the diversity of objects is large and already exceeds that of the MeV-GeV catalogs.

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