.

SUMMARY

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ABSTRACT. An overview of some of the main topics addressed at the Les Houches NATO winter school 'The Gamma-Ray Sky with COMPTON GRO and SIGMA' is presented. Results from GRO, SIGMA, and also Cerenkov telescopes are summarized. The topics covered are γ-ray bursts, active galactic nuclei, γ-ray lines, galactic continuum emission, pulsars, black hole candidates, accreting pulsars and new techniques.

1. Introduction

The two weeks of lectures gave an excellent overview of the current status of γ-ray astronomy, many lecturers taking the opportunity to go 'back to basics', providing a good introduction to the topics for the non-specialist. The wealth of new information on the γ-ray sky provided by COMPTEL, SIGMA, the Whipple observatory and other experiments described at this meeting has (as is to be expected) raised at least as many questions as it has answered.

Among the striking observational results are the isotropy and sheer variety of γ-ray bursts, the variability of the extragalactic γ-ray and the galactic hard X-ray sky, the high efficiency of some pulsars for γ-ray production, the direct evidence for nucleosynthesis via various nuclear lines and the opening of the TeV window both galactic and extragalactic. It is perhaps worth summarizing a few of the outstanding questions which are now open. At the top of the list must be the distance and nature of the γ-ray bursts, followed by the processes producing γ-rays from AGNs (electrons, protons, jets ?), the origin of the positrons generating the diffuse 511 keV line, the sites of ^{26}Al production, the γ-ray emission mechanism in pulsars (outer gap/polar cap/other ?), the nature of the unidentified EGRET galactic sources, the origin of the hard X-ray and γ-ray backgrounds; and the processes producing the Orion nuclear de-excitation lines.

This brief resumé of some of the topics covered may serve to give some flavour of the material as a preview to reading the full story elsewhere in this book.

2. Bursts

The number of bursts observed by BATSE is approaching 1000. They are unique in astronomy in terms of intensity (up to 10^{-3} erg cm^{-2} s^{-1}), appear to be one-off events (no proven repetitions up to now), and appear only at γ-ray energies. They have a five orders-of-magnitude range of durations (5ms to 500 sec). The time profiles show amazing diversity, from smooth to very spiky, some showing a fast rise followed by exponential decay. A few have been detected by EGRET, e.g. that of 3 May 1991 which has a 10 GeV photon appearing 84 seconds after the BATSE burst. General trends can be discerned: shorter bursts tend to have harder spectra, and there is an evolution from hard to soft during the burst. There is evidence that weaker bursts have longer durations. The repetition time scale is at least 10 years; COMPTEL has recently found a possible candidate for a repetition.

The angular distribution is highly isotropic independent of whether tested in galactic coordinates or by system-independent methods. The logN-logS plot shows the expected $-\frac{3}{2}$ law at high intensities and a clear deficit at low intensity; $< \frac{V}{V_m} >= 0.32 \pm .01$ is significantly less than the Euclidean value of 0.5 indicating a spatially bounded distribution.

The spectra tend to be simple, with typically a break in the 50-500 keV range; those observed by COMPTEL have typical breaks around 2 MeV, while some have unbroken power-laws up to GeV as observed by EGRET. Power-law indices range from -3 to greater than 0. There is no evidence for lines, although they would be expected to have been easily seen based on the reports from some previous instruments.

The hardest problem for Galactic models is clearly the isotropy, which requires an extended halo of at least 100 kpc size. The fact that no burst clustering is seen around M31 or the LMC poses another difficulty: if the galaxy contains the sources then they should be present and visible in these galaxies also. Cosmological models provide the most straightforward interpretation; models without evolution and with a maximum redshift around z = 1 (but not greater than z = 3) can reproduce the logN-logS plot satisfactorily. The current paradigm of neutron-star mergers requires one burst per galaxy per million years which is plausible based on the expected merger rate.

The search for counterparts is an active area at all wavelengths. In particular for sources with sub-degree error boxes from triangulation by the interplanetary network, optical searches using archival plates and followup observations put limits of 20-24^m on non-contemporaneous counterparts, while sky patrol plates give a limit of 4-10^m for contemporaneous events. These limits already allow some candidate source populations to be excluded, for example QSOs would have been identified. Soon (the BACODINE project) it will be possible to obtain positions within seconds from BATSE real-time data and transmit these to telescopes for rapid followup.

3. AGN

Detections of active galactic nuclei have been reported by all the COMPTON instruments. EGRET has detected about 27 (>100 MeV), which fall into the class of flat-spectrum, radio loud, highly variable objects (QSOs and BL Lacs); no Seyferts were detected. In contrast OSSE detects about 19 AGNs in the 50 - 500 keV range of which most are Seyferts and only 3 are QSOs. COMPTEL (0.7-30 MeV) detected 3 of the EGRET QSOs (3C273, 3C279 and PKS0528+134), Cen A, and in addition other candidate identifications which may indicate a class of 'MeV blazars'. One of these (candidate sources: CTA 102, 3C454.3) is also a weak EGRET source. BATSE has also detected 3 AGNs using the earth-occultation technique. SIGMA detections of 3C273, Cen A and Seyfert NGC4151 have been made. At TeV energies the Whipple detection of MRK421 is so far the only positive results for an extragalactic source, presumably because of the strong absorption by the intergalactic radiation field.

The OSSE average Seyfert spectrum based on 15 objects shows clearly that a thermal fit is better than a power-law, with kT = 30-50 keV depending on whether a Sunyaev-Titarchuk or exponential spectrum is fitted. No Seyferts have been detected by COMPTEL to date, which reflects the thermal nature of the emission from these objects. The paradigm is Compton scattering of soft photons by hot ($\approx$ 40 keV) thermal electrons around an accreting black hole; Monte-Carlo computations of spectra are important here to evaluate accurately the observable spectrum for the Sunyaev-Titarchuk model, as a fit to the NGC4151 spectrum (Dermer) demonstrates.

The most striking feature of the EGRET QSOs is their variability: e.g. 3C279 varies by a total factor of 40, and the time scales involved are days to months. PKS0528+134 has been observed to be comparable to Geminga in flux on one occasion. Evidence for long-term variability over years is found for 3C273 which appears now to be significantly weaker than in the COS-B epoch (1975-82). The spectra are generally consistent with power-laws but with a wide range of indices (-1.6 to -2.6 photon index); however the power-law behaviour does not generally extend to lower energies; the COMPTEL and OSSE fluxes and flux limits show that there is often a break at a few MeV. The combination of EGRET (0.05-4 GeV) and Whipple (.5-3 TeV) data for MRK421 indicates an unbroken $E^{-2.05}$ power law from 100 MeV to 1 TeV.

Theories for the γ-ray emission from QSOs have in common the necessity to invoke beaming and Doppler boosting to explain the high fluxes and rapid variability without running into problems of γ-γ absorption in the source. Models have in common a requirement for an energy source in the form of a supermassive black hole (10^6-10^8 $M_\odot$). Whether the relevant accelerated particles are leptons or hadrons is not known and several models invoking each have been proposed. To mention just one of the many models discussed, inverse-Compton scattering of soft photons from the accretion disc by electrons in the relativistic beam is a scenario which explains naturally the dominance of objects with apparent radio superluminal motions as γ-rays sources. A predicted spectrum based on this mechanism for 3C279 (Dermer) can reproduce the observations over a wide range of energy. The goal is clearly to integrate the γ-ray emission into the unification schemes which have been proposed to explain radio galaxies, QSOs and Seyferts as essentially the same phenomenon differing only in the aspect from which they are observed.

The OSSE spectra indicate that the hard X-ray background may well be dominated by Seyferts. Using the NGC4151 spectrum with evolution out to z=4 gives a good fit to the spectrum (Zdziarski); however this is only one of several possibilities. The contribution of AGNs to the high energy γ-ray diffuse extragalactic background is at present unclear; estimates are made difficult by our lack of knowledge of the duty cycle of the variability. Extended observations of selected regions to monitor variablity are being carried out by COMPTON and this will provide essential data for this problem. In any case it is likely that a large fraction of the background is attributable to QSOs.

4. Gamma-ray lines

OSSE has accumulated a large amount of data on the distribution of the diffuse 511 keV positron annihilation line in the inner galaxy; GRIS and HEXAGONE provide high energy-resolution (3 keV) data sampled at a few locations. In the OSSE observations the line and the the positronium continuum (fraction 0.96) are always visible; however OSSE finds no evidence for a time-variable line in 180 days of observation, nor an 170 keV backscatter or redshifted annhilation features in the galactic centre region.

The origin of the positrons may be β-decay of radioactive nuclei produced in novae and/or supernovae in which case models based on the distribution of novae, supernovae or their tracers are appropriate. The conclusion from the OSSE data is that a spheroidal component with a radius of 10^o is required in addition to the 80^o wide in longitude component characteristic of novae. A point source at the centre is not required by the OSSE data in the context of these models.

GRIS and HEXAGONE observations resolve the 511 keV line and thereby allow a limit of 7 10^4K on the temperature of the hot component of the emitting region. Another possible origin for the positrons is related to pair production in black holes in objects like the 1E source; depending on their (unknown) duty-cycle a few such objects in the galactic centre region could perhaps produce the required 3 10^{43} positrons s^{-1} and fill the bulge. In 1989 HEXAGONE detected the 511 keV line and a 170 keV feature which could be attributable to Compton backscatter in a compact source.

^{26}Al maps of the galactic plane from COMPTEL show clearly the extended nature of this emission, which appears to be asymmetric in longitude and rather clumpy; emission possibly associated with the Vela SNR has also been detected. Because of the 10^6 year decay time of ^{26}Al we are obviously here seeing recent nucleosynthesis. Novae should produce a much more homogeneous, smooth and symmetric distribution than that observed by COMPTEL. The most probable origin for the ^{26}Al appears to be supernovae. Supernova nucleosynthesis models starting with 11-40 $M_\odot$ zero-age main sequence stars and various metallicities have been computed by the Santa Cruz group using the KEPLER code which follows a 200 isotope network through advanced stellar evolution and the supernova explosion. The yield from a type II SN is a rapidly varying function of mass; the maximum yield per event is about 10^{-3} $M_\odot$ of ^{26}Al for high progenitor masses. Galactic chemical evolution models can be computed which reproduce the observed isotopic abundances; based on these the total ^{26}Al from all SN types is about 2 $M_\odot$, similar to the value required by COMPTEL data. However other candidate sites (Wolf-Rayet stars, novae, cosmic-ray spallation) must also be considered.

The detection of the 1.16 MeV ^{44}Ti from the Cas A SNR (COMPTEL) presents a milestone for our understanding of nucleosynthesis. Although there is a possible conflict with OSSE results from the same object, this detection confirms our general belief in supernova nucleosynthesis via another radioactive tracer. The implied mass of ^{44}Ti produced in the Type 1b supernova is 3 10^{-4} $M_\odot$. The yield is critically dependent on how much mass is ejected. One problem is to explain the lack of a historical observation of the supernova (age $\approx$ 320 years, distance $\approx$ 3 kpc) which should have been bright optically (0-1^m even with the estimated 5^m of extinction) if this amount of ^{44}Ti was produced. The search for other sources of ^{44}Ti in the galaxy continues as both the galactic ^{44}Ti content and the SNII rate have suggested that several objects in the galaxy should be visible.

The recently reported $^{12}C^{*}$ (4.4 MeV) and $^{16}O^{*}$ (6.1 MeV) nuclear de-excitation lines from the Orion molecular complex (COMPTEL) were the subject of much interest. The conclusion seems unavoidable that heavy cosmic-rays at low energies (< 10 MeV/nucleon) are involved rather than high fluxes of protons exciting interstellar matter, which would produced excessive ionization. Computations in which both cosmic-rays and target have supernova ejecta composition were presented (Ramaty) which for a cosmic-ray spectrum with a cutoff at 3 MeV/nucleon can reproduce the observed spectrum. Very large cosmic-ray fluxes, a factor of 30 above the interstellar value, are in any case required.

5. Galactic continuum emission

The potential of EGRET data for the study of the diffuse galactic continuum emission is enormous, and first results were presented (Michelson). Predictions based on a gas (atomic and molecular hydrogen) model with some cosmic-ray/gas coupling fit the observations at least on a large scale. From COS-B analyses the main conclusions were the rather small galactocentric emissivity gradient which is hard to reconcile with a distribution of cosmic-ray sources like SNR, and the determination of the conversion factor to be used in estimating molecular hydrogen column densities from CO surveys. Up to now the EGRET data give no reason to doubt the validity of these basic results from COS-B, but given the quality of EGRET data there is the potential for a far more accurate analysis. The question of the contribution from point sources can now be better addressed. At lower energies the COMPTEL emissivity spectrum of the diffuse emission is compatible with expectations for bremsstrahlung from cosmic-ray electrons, based on propagation models with ionization losses. However other components certainly must contribute, including point sources and inverse-Compton emission, and much more work is needed.

EGRET observations of the ρ-Oph molecular cloud reveal the presence of a source identified as a flat spectrum radio QSO, which obviously complicates the interpretation. Taking this source into account the emission from the cloud is consistent with a normal cosmic-ray density and gives a value of CO-to-H_2 conversion factor 1.3 10^{20} mols. cm^{-2}/(K km s^{-1}) , lower than the COS-B value 2.3 10^{20} mols. cm^{-2}/(K km s^{-1}) for the galactic plane .

The EGRET detection of the Large Magellanic cloud allows the first estimate of cosmic-ray flux in an external galaxy: it appears consistent with the flux in our galaxy. In contrast the upper limits for the SMC indicate a much smaller flux and this is perhaps related to the lack of containment of cosmic-rays in this system.

6. Pulsars, SNRs, unidentified sources

All COMPTON instruments have made detections of at least two isolated pulsars: BATSE (Crab, 1509-58), OSSE (Crab, Vela, 1509-58), COMPTEL (Crab, Vela, 1509-58), EGRET(Crab, Vela, Geminga, 1706-44, B1055-52).

The hardest spectrum is that of B1055-52 (-1.2 photon index >100 MeV); Geminga has also an extremely hard spectra, and like Vela exhibits a cutoff at the highest

EGRET energies. A spectrum of Vela based on OSSE, COMPTEL and EGRET data shows a flattening below 10 MeV; for Geminga, which is not detected by COMPTEL even above 10 MeV the limits are only just consistent with a continuation of the spectral shape to MeV energies and indicate a falloff here too. Comparison of the Vela spectrum with predictions based on outer-gap and polar-cap models do not allow these to be distinguished with the present data. The interpulse emission spectrum is flatter than the main peaks by about 0.5 in spectral index; the fine phase-resolved spectroscopy now possible with EGRET should provide a critical test for theories in the future.

There is a clear trend for the γ-ray efficiency to increase with pulsar age: the most efficient being B1055-52 and Geminga ($\eta \approx 1$), and the least being 1509-58 which also has the largest known spin-down rate of any pulsar.

Progress in multi-wavelength observations of isolated neutron stars continues, with six optical (three with observed pulses) and thirteen keV X-ray (nine pulsed) detections to date. PSR1509-58 has now been detected (Bignami) at 22^m with the ESO NTT telescope and timing observations are planned. A candidate optical identification of PSR0656+14 awaits confirmation.

The proper motion of the Geminga optical counterpart over the period 1984-1992 is $.17''$ per year which indicates a distance of order 100 pc; we now have the exciting prospect of a parallax measurement with HST. A plausible case can be made for the association of the local superbubble with the supernova event which produced Geminga ; in this scenario the explosion took place tens of pc from the Sun and the neutron star travelled away from us to its present position at $\approx$100 km s^{-1} over the last 3 10^5 years. Of course the basic uncertainties are the present distance and the radial velocity of Geminga.

The X-rays have a two-component thermal spectrum, the components being plausibly related to the emission from the entire neutron star surface and from the polar cap. The multiwavelength data are clearly essential to distinguish polar cap and outer gap models. A recent new contender for the γ-ray emission, the resonant Compton-induced pair cascade, was also presented (Dermer).

Unpulsed TeV emission from the Crab (hence presumably the nebula) reported at 45σ by the Whipple observatory has now also been detected by five other experiments (ASGAT, Themistocle, HEGRA, CANGAROO, GAMMA). No pulsed signal is seen by these experiments. The model by Harding and de Jager successfully reproduces the nebular TeV spectrum as inverse-Compton from interactions of electrons accelerated by the pulsar wind to energies as high as 10^{15} eV, the GeV γ-ray spectrum being the result of synchrotron radiation from these same electrons.

PSR 1706 has been detected at TeV energies by the CANGAROO telescope at 10σ; no timing result is however reported.

The COS-B source 2CG135+1 has been confirmed by EGRET and the improved position allows a more certain identification with the Gregory-Taylor variable radio object; it may be a young pulsar and a B0 star in a binary system. This source has also been detected by COMPTEL.

The EGRET catalog contains about 40 sources near the galactic plane most of which are unidentified. Most of the COS-B sources are confirmed indicating that they are stable over long time periods. What are these sources ? The latitude distribution indicates distances 2-6 kpc and the observed fluxes gives luminosities 10^{35}- 10^{36} erg

s^{-1}; old pulsars like Vela or Geminga are too weak; young pulsars and Crab-like plerions are obvious candidates but normal SNR are also a possibility.

A source consistent with the GC (within 0.2^o) has also been discovered by EGRET. The nature of this source is unclear but its position rules out the 1E source and it is hard to explain it in terms of cosmic-ray/gas interactions.

7. Black hole candidates

One of the highlights of the school was a movie based on SIGMA images of the galactic centre region, showing sources appearing and disappearing in a spectacular way and graphically illustrating the enormous variability in the hard X-ray sky. Spectral imaging by SIGMA is a powerful technique especially in regions like the galactic centre where the presence of several sources can confuse other instruments. BATSE is able to do continuous monitoring of both the persistent and transient sources by the earth-occultation technique.

These objects are typically black-hole candidates implying binaries with high mass, an ultrasoft spectral state, hard X-ray spectra, and sometimes QPO activity and occasionally bursts of annihilation line radiation. The spectra are harder than binaries containg neutron stars. The list of such objects which are persistent or recurrent includes Cyg X-1, GX339-4, GRS1758-258, GRS1915+105 and the 'great annihilator' 1E1740.7-258. Cyg X-1, the prototype BH candidate (mass $\approx 6M_\odot$) has been continuously monitored by BATSE using the earth occultation technique. It is normally found in the low flux γ_1 state and occasionally in higher flux (γ_2,γ_3) states; but in February 1994 it switched to a uniquely low state which triggered a 'target-of-opportunity' observation by COMPTON; it will be interesting to see what OSSE and COMPTEL observe in this state. OSSE, COMPTEL and SIGMA find evidence for a hard tail to the spectrum but no 'MeV bump' in the γ_1 state of the type reported in earlier balloon experiments. Strong variability is also found at the high energy end of the spectrum. The standard (Sunyaev and Titarchuk) model involves Comptonization of ambient soft photons by hot (40-80 keV) electrons. This model falls short of accounting for the spectrum above 300 keV, although more accurate Monte Carlo modelling of the Comptonization gives better fits. The COMPTEL detections up to 2 MeV provide support for a model involving much higher electron temperatures (200 keV) in an accretion disk corona.

Turning to the source 1E1740.7-258, in SIGMA observed a broad feature around 500 keV in 1990, and an excess emission around 350-380 keV for several hours on three occasions in 1992; a puzzle is the lack of a corresponding signal in the contemporaneous 1992 OSSE data for the galactic centre region.

GRS1915+105 exhibited a 450 day long outburst in 1992-93, and another one was reported by BATSE to have begun in Dec 1993.

In addition to the persistent or repetitive sources are the class of transients ('X-ray novae') such as nova Muscae 1991, Persei 1992, Ophiuchi 1993 and Velorum 1993. These show an exponential decay on a timescale of weeks after the initial outburst, and sometimes secondary maxima. A spectral softening during the rise is followed by a hardening during the decay. In the case of nova Muscae, a transient excess at 481 keV consistent with redshifted annihilation-line radiation and a feature at 200 keV possibly attributable to backscatter was observed for some hours by SIGMA.

A hard spectrum was observed for nova Persei by SIGMA, BATSE and OSSE, and the COMPTEL detection also indicates a non-thermal tail; there is also evidence for QPO activity at 0.2 Hz.

8. Accreting pulsars

Also referred to as 'X-ray pulsars' 30 of these pulsars in binary systems are known, about 20 have orbital parameters determined and 14 can be continuously monitored by BATSE using sophisticated time and frequency domain filtering techniques on the raw time series from the detectors (Prince). New or improved orbital parameters are obtained from analysis of the periodic Doppler shifting of the pulsar period. Five of the systems observed by BATSE are also eclipsing. Known accreting pulsars have periods ranging from 70ms to 840 s. A classification based on the pulsar period and the orbital period divides these objects into wind-fed, disk-fed and Be binary systems. The pulsar periods for the BATSE systems span the range seconds to hundreds of seconds, the orbital radius tens to hundreds of light-seconds. A couple of examples: the BATSE discovery GRO J1008-57, detectable for a month, had a pulsar period of 93 seconds and an orbital period 100-200 days and is probably to be classified as a Be binary. Another system which has had its orbital parameters determined by BATSE, OAO1657-415, has a companion with mass 14-23$M_\odot$ and radius 21-35$R_\odot$; based on the spin-period/orbital period classification it is either the fastest wind-fed or the slowest disk-fed system, or probably an intermediate type.

The continuous monitoring by BATSE allows long-term studies of accretion torques in several of these systems via the secular variation of the spin period, which exhibits behaviour ranging from monotonic spin-up to frequent changes of sign.

This is a very exciting and promising field, and we can expect much more to come.

9. Techniques

The recent advances in the field of TeV astronomy herald something of a revolution in this subject, and this was reflected in the attention devoted to Cerenkov techniques. The development of imaging detectors at the Whipple observatory has led to dramatic improvement in rejection of nucleonic showers and allows a detection of the Crab in a few hours; the current significance quoted is 45σ. The next generation of detectors is coming. The new GRANITE facility on Mt Hopkins with 10m and 11m telescopes giving stereoscopic imaging of showers is about to go into operation. Other projects include HEGRA (Canaries: 5$\times$ 3m telescopes), CANGAROO (Australia: 3.8m, high resolution), Durham Mk IV (3$\times$ 40 m^2), ASGAT and Themistocle (France, Themis site: 7$\times$ 7m, 18$\times$ 0.8m).

The ASGAT and Themistocle arrays use wavefront timing; this technique has already proved itself with a detection of the Crab. Also proposed for Thémis are the CAT imaging telescope (16 m^2) and an ambitious plan to use the 200 heliostats of the Solar Array to achieve 10^4 m^2 area which would open the way to ground based detectors in the tens of GeV range, thus closing the gap with space observatories.

The list of highly significant TeV detections is still short (Crab, MRK421, PSR1706-44) but the large number of new experiments gives hope for a steady growth. An important problem is still the absolute energy calibration which can lead to large deviations between different experiments; optimism was expressed that the situation here too will improve.

Other techniques related to satellite observations were presented. Frequency analysis of BATSE data has reached a high degree of sophistication as the large number of accreting pulsars studied shows. Generation of wide-field images from BATSE earth-occultation data is a new example of an advanced method for exploiting the data beyond the original conception for such an instrument. The first images shown indicate that this will yield important results in the future. Now OSSE too is using an indirect imaging technique which uses data from many observations to construct images of fields containing several sources, as was illustrated with a map of the Virgo region. Similarly the use of the SIGMA instrumental 'sidelobes' for imaging strong sources far off-axis, bursts, and now the diffuse galactic hard X-ray emission about which very little is known, is an unexpected development coming late in the mission based on long experience with the data analysis.

10. Conclusion

Gamma-ray astronomy is flourishing at the present time; COMPTON will continue to return results for several more years; SIGMA will unfortunately end in 1994 but the enormous data volume will take years to fully analyse. For the near future of low energy spectroscopic γ-ray astronomy the INTEGRAL mission due for launch in 2001 is already the major occupation of many people at this school. TeV astronomy is taking off. Other new developments such as silicon-strip telescopes are in a more prototyping stage but indicate the interest in using new technology to improve sensitivity and resolution. So there will be no lack of excitement for the next generation of γ-ray astronomers.