The Extreme Universe: Some Views From Here

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ABSTRACT Forty years have passed since the first Explorer orbiting observatory - the 1958 mission used to discover the Van Allen radiation belts outside the atmosphere - ushered in the modern age of space science. Even though in situ observations of outer space are still restricted to measurements made within the solar system, we now have access to a wide range of cosmic signals, extending from the well understood microwave photons indicative of the earliest epoch of the universe to those apparently inexplicable ultra-high energy extragalactic cosmic ray particles that are too energetic (up to 50 Joules/each) to have survived passage through a cosmological extent of the pervasive thermal relic radiation field. In this lecture the extremes of cosmic ray physics are discussed within the context of particles having the lowest energy (down to $\sim 10^{3}$ eV/nucleon) and highest energy ($> 10^{20}$ eV), emphasizing those aspects of astronomy, particularly gamma-ray and x-ray, that appear to be especially revealing for these regimes.

KEY WORDS: cosmic rays - gamma rays - x-rays - black holes

1. INTRODUCTION

Over eighty years ago Victor Hess, standing in a balloon-borne gondola, used simple electrosopes to discover ionizing radiation coming from the residual atmosphere above him, thereby initiating the rich fields of high energy physics and high energy astrophysics. Now we are ready to begin the next century with major space-borne astronomical observatories for cosmic x-rays and gamma-rays with powerfully instrumented sophisticated missions such as AXAF, XMM, Astro-E and INTEGRAL. In this lecture I trace the evolution of high energy astrophysics within the context of cosmic X and gamma radiation, emphasizing those aspects that are especially relevant to cosmic ray research. To a large extent it parallels my own post-graduate involvement in the field over the last four decades and reflects the bias of my particular interests.

For the universe traced by baryonic matter, the presently well defined cosmic X/gamma-ray background has provided a physically critical integral measure of a vast intervening history, particularly for AGN evolution. The implications of this comprehensive measure of accretion powered AGN activity during all relevant earlier epochs support other recent evidence for a local abundance of currently inactive supermassive spun-up black hole quasar remnants, candidate dynamos for the acceleration of cosmic rays. Finally, I tell of possible space-borne observatories
for measuring, from topside vantage points, the atmospheric fluorescence arising from cosmic ray initiated air showers and how they could be used to determine the arrival directions of the very highest energy events, ones that might well be correlated with those candidate sources associated with supermassive black hole galactic nuclei.

2. BACKGROUND

In 1928 Robert Millikan proclaimed that cosmic rays are neutral quanta, the “birth cry” of atoms created by elemental synthesis from primordial hydrogen spread throughout the universe. Seventy years later, at the recent 1998 APS meeting in Columbus, Srinivas Kulkarni presented a lecture entitled “Gamma Ray Bursters: Dying Cries from the Distant Universe”. This remarkably glorious era for high energy astrophysics all began with little fanfare on 7 August 1912 when a balloon-borne gondola ascended from a field near Aussig, Austria; in the gondola were the physicist Victor Hess, two helpers and three electrosopes. As expected, for the first kilometer the electroscope discharge rate decreased somewhat with altitude as the gondola moved away from the presumed traces of radioactivity in the earth’s crust. However, at higher altitudes the trend reversed; at an altitude of about 5 kilometers the rate was four times faster than on the ground. Quite correctly, Hess concluded that this arose from an ionizing flux coming from above and conjectured that it was ultimately due to penetrating radiation falling upon Earth from somewhere beyond the atmosphere. During the next three decades, however, the exact nature of the primary radiation remained a mystery [for fascinating accounts of this early history see “Cosmic Rays” by Rossi (1964) and Friedlander (1989)]. First of all, was this radiation neutral (e.g., “ultra” gamma-rays) or charged? For a substantial time there were two schools on this. As already noted, Millikan (who invented the name “cosmic rays”) favored the interpretation that they are neutral. Arthur Compton, his collaborators and eventually other researchers (including Millikan) concluded that the radiation was positively charged, as deduced from using the earth’s dipole field as a magnetic analyzer. Today we know that the cosmic ray flux also involves ionizing components of negative charges (electrons) and photons (gamma rays and X-rays) as well as nuclei; Table 1 gives the various components, listed in order of energy flux impinging upon the atmosphere.

In order to provide some historical perspective on the opening of new observational windows, it is interesting to consider some of those modern cosmic discoveries readily categorized as “expected” or “unexpected” (see Table 2). Although we anticipated neither gamma ray bursts nor extragalactic blazar gamma sources, we definitely did expect diffuse galactic gamma rays. After all, gamma radiation is a necessary consequence of high energy cosmic ray protons (> 0.3 GeV) interacting with interstellar matter; the resultant neutral pion products yield a flux of photons > 100 MeV well traced over the entire Milky Way via the EGRET instrument on CGRO (Fichtel et al. 1993; Hunter et al. 1997). In sharp contrast, X-ray astronomy came as a complete surprise. We knew of the interstellar medium (ISM) but
Table 1. Cosmic Radiation: Principal Ionizing Components (energy flux order)

| No. | Component                                      | Energy Flux Order |
|-----|-----------------------------------------------|-------------------|
| 1   | Nucleonic (galactic)                          | $E > 20 \text{ MeV/nucleon}$ |
| 2   | Electron (galactic), relativistic             |                   |
| 3   | X-rays (extragalactic)                        |                   |
| 4   | X-rays (soft galactic)                        |                   |
| 5   | Gamma-rays (diffuse galactic)                 |                   |
| 6   | Gamma-rays (extragalactic)                    |                   |
| 7   | X-rays (galactic binaries, SN...)             |                   |
| 8   | X-rays (diffuse non-thermal galactic):        |                   |
|     | - subrelativistic cosmic ray bremsstrahlung?  |                   |
|     |     - $h\nu \geq 10 \text{ keV} \rightarrow E \geq 20 \text{ MeV/nucleon}$ |           |
| 9   | Cosmic rays (extragalactic)                   | $E > 10 \text{ Joules/each}$ |

Did not expect to encounter a local hot X-radiating interstellar plasma, now known from ROSAT mapping to be a lasting imprint of past explosive events in our region of the Milky Way (Snowden et al., 1997). Who would have thought that the first direct evidence for the shock acceleration of relativistic cosmic rays would come via X-ray astronomy? Yet, ASCA X-ray data on the supernova remnant SN1006 did just that (Koyama et al., 1995). It’s becoming very clear that the charged particle and electromagnetic components of cosmic radiation are inexorably intertwined; as emphasized in this presentation, complementary studies of them can be very revealing.

Astronomy is replete with examples in which the most significant advances or the most astounding discoveries arose with the opening of new observational windows, partly by design and partly by chance. We cite two recent examples from high energy astrophysics; see Table 2 for others. RXTE was designed to have the high throughput and timing capability needed to measure rapid variability in low-mass X-ray binaries, but it was the unexpected millisecond oscillations observed that opened up a fundamental new phase in X-ray astronomy, one that probes neutron stars in the dynamical and gravitational regime needed to constrain the equation of state of neutron-star matter and to measure the neutron star mass in the strong-field limit of general relativity (Kaaret, Ford & Chen, 1997; Zhang, Strohmeyer & Swank, 1997). Clearly, the particular complement of synergetic instruments aboard BeppoSAX is the main factor that has made it possible to exploit the unexpected X-ray afterglow of gamma-ray bursts for providing sufficiently prompt accurate positions, those needed for the precise optical measurements that are establishing their cosmological origins (Costa et al., 1997; Metzger et al., 1997).
Table 2. Historical Perspective: New Windows on the Universe: Cosmic Discoveries

| EXPECTED                        | UNEXPECTED                                      |
|---------------------------------|--------------------------------------------------|
| An interstellar medium          | A hot x-radiating plasma                        |
| Gamma-ray Astronomy             | Gamma-ray bursts                                |
| Black holes                     | X-ray Astronomy                                 |
| Neutron Stars                   | Pulsars                                         |
| Gravitational radiation         | Binary pulsar                                   |
| Gravitational lensing           | Dark matter                                     |
| The Milky Way                   | Galaxy clustering                               |
| Evolution                       | Radio Astronomy                                 |
| “Big Bang” relic Cosmic         | Supermassive Black Hole Galactic Nucleus        |
| Microwave Background            | A distortionless black body spectrum            |
| Primordial gas in clusters      | Iron K-line emission in clusters                |
| Baryon Symmetry                 | Matter, matter everywhere                       |
| Extragalactic Cosmic Rays       | Too energetic                                   |

Astrophysical studies from space platforms began with the Explorer 1 discovery of the Van Allen radiation belts in 1958 (Van Allen, Ludwig, Ray & McIlwain, 1958); Table 3 lists some of the most significant space physics milestones since then. Although the advent of orbiting observatories brought us above the atmospheric barrier that had previously hampered the study of primary cosmic rays, this discovery made us aware of the radiation hazard these belts posed for the sensitive detectors involved and made us consider how to minimize such encounters. The 1959 detection of the solar wind plasma with Lunik I & II (Shklovskii, Moroz & Kurt, 1960) and studies of solar driven cosmic ray modulation effects of the wind (Balasubrahmanyan, Boldt & Palmeira, 1965, 1967) made us realize that getting above the atmosphere was not sufficient and that, eventually, this additional formidable barrier would have to be surmounted for the proper study of the interstellar cosmic ray flux. The first clear measurements of the low-energy spectrum of cosmic rays, those arriving here at 1 AU, involved observations made far from Earth, albeit well within the heliosphere (McDonald & Ludwig, 1964). So far, deep space probes have yet to reach bonafide interstellar space (> 120 AU), beyond the reach of solar wind effects (Axford, 1992). By the year 2000 the distances observed with Voyagers 1 & 2 will be 76 and 61 AU respectively. However, the solar wind has to this day still prevented us from measuring flux values for low rigidity cosmic rays at all close to being as large as those values expected for the corresponding interstellar particles outside the heliosphere (McDonald, 1998). After reaching beyond the heliosphere, the ultimate remaining barriers in directly detecting an all-inclusive sample of sub-
Table 3. Space Physics Chronology: 1958 -

| Year | Event Description | Notes |
|------|-------------------|-------|
| 1958 | Van Allen radiation belts | space hazard |
| 1959 | Solar wind | cosmic ray barrier |
| 1960 | Cosmic ray electrons | spectral neutrality |
| 1962 | Cosmic X-rays | accretion, black holes |
| 1963 | Quasars | compact galactic nuclei |
| 1964 | Subrelativistic cosmic rays | ISM ionization & heating |
| 1965 | Microwave background | early universe |
| 1968 | Pulsars | neutron stars |
|  & Solar neutrinos | nuclear furnace |
|  & Hot ISM | soft X-radiation |
| 1972 ('61) | Cosmic gamma-rays | galactic cosmic ray tracer |
| 1973 ('68) | Gamma-ray bursts | new physics /astrophysics? |
| 1973 | Fe X-ray K lines | hot plasma spectroscopy |
| 1974 | Binary pulsar | gravitational radiation |
| 1978 ('33) | Missing mass | galactic, clusters |
| 1984 | $^{26}$Al gamma-ray line | nucleosynthesis tracer |
| 1985 | Gravitational lensing | dark matter |
| 1987 | Non-solar neutrinos | SN1987A |
| 1991 | Extragalactic cosmic rays | new physics/astrophysics? |
| 1992 | Blazar gamma-rays | beamed emission |
| 1993 | Machos | massive compact halo objects |
| 1994 | Microquasars | relativistic stellar jets |
| 1995 | Cosmic ray accelerator | SN1006 |
| 1996 | Helioseismology | solar inner structure |
|  & HST deep field | early star/galaxy history |
| 1997 | Gamma burst afterglow | cosmological origin |
|  & Millisecond QPOs | general relativity strong field limit |
relativistic cosmic ray nuclei are low energy and short lifetime. The average high energy cosmic ray traverses $\sim 10 \text{ g/cm}^2$ of ISM matter in $\sim 10^7$ years before being lost (e.g., by escape from galactic confinement). Hence, for a cosmic ray particle to reach our neighborhood of the Milky Way from its place of origin there must be sufficient energy to traverse a minimal ISM columnar density of matter and, if a radioactive nucleus, sufficient lifetime ($\geq 10^7$ years) before decay. As we shall see in the next section (Section 3) the emission of characteristic X and gamma rays in basic radiative processes is crucial in providing us with the means needed to achieve remote sensing of otherwise inaccessible cosmic rays and thereby obtain a significantly more comprehensive sample.

3. CONNECTIONS

The lowest energy cosmic rays in the Milky Way are to be found among those fresh products of nucleosynthesis that have propagated into the interstellar medium but have not yet become thermalized. The quintessential example is the $\beta$-radioactive nucleus $^{26}$Al first observed with the solid-state (Ge) spectrometer on HEAO-3 (Mahoney, Ling, Wheaton & Jacobson, 1984) by detection of the 1.8 MeV gamma ray spectral line from an excited state of the daughter $^{26}$Mg. Having a relatively short average decay lifetime ($1.0 \times 10^6$ years), an order of magnitude less than the confinement lifetime of energetic cosmic rays, and suprathermal velocities of only $\sim 500 \text{ km/s}$ (Naya et al., 1996), the distribution of such $^{26}$Al provides a current snapshot of nucleosynthesis sites throughout the galaxy, as obtained by imaging of 1.8 MeV gamma rays with the COMPTEL instrument on CGRO (Diehl et al. 1995). The next generation of gamma-ray spectrometers, such as the INTEGRAL spectrometer (von Ballmoos, 1995), should give the improved maps needed to more completely trace the current nucleosynthesis activity in the Milky Way, especially for regions of relatively low surface brightness. This nucleosynthesis of $^{26}$Al in stars and stellar explosions is to be distinguished from that produced at much higher energies as fully stripped spallation products from energetic cosmic ray transport in the ISM; Simpson and Connell (1998) have suggested searching the galactic halo for a highly broadened 1.8 MeV line from such transrelativistic nuclei. In sharp contrast, it’s important to note that a subrelativistic $^{26}$Al ion injected into the ISM rapidly reaches a charge equilibrium, determined solely by its velocity, via the competing processes of electron capture and loss (Pierce & Blann, 1968). For aluminum at 500 km/s ($\sim 1 \text{ keV/nucleon}$) the average effective charge of the ion is thereby only $\sim 0.5$ (i.e., essentially a neutral atom). In this situation we must consider the alternate decay mode of $^{26}$Al to $^{26}$Mg via electron capture (rather than positron emission), one which then occurs 18% of the time. The attendant removal of a K shell electron leads to a 1.25 keV K\linebreak[0]α X-ray from the atomic transition that replaces the missing K shell electron for the Mg daughter. This narrow X-ray spectral line is a complementary tracer of subrelativistic $^{26}$Al in the local Milky Way (within $\sim 3 \text{ kpc}$), one that has the potential of providing the high resolution spatial/spectral measurements needed to determine the detailed distribution, velocity, ionization
state and chemical setting of these freshly synthesized nuclei. In particular, it has been suggested (Lingenfelter, Ramaty & Kozlovsky, 1998) that the subrelativistic $^{26}\text{Al}$ detected actually resides in rapidly moving grains of $\text{Al}_2\text{O}_3$. We should note that unit optical depth for the photo-absorption of a 1.25 keV X-ray in $\text{Al}_2\text{O}_3$ would be 1.6 $\mu$m, not very much more than the largest sizes of usual grains; hence, this presents us with the possibility of using the x-ray signal for some direct chemical diagnostics.

Preliminary results from COMPTEL observations of some galactic regions suggesting an enhancement in 3 - 7 MeV gamma-ray emission (Bloemen, 1994) have led to the realization that such a signature could indicate the presence of much freshly synthesized $^{12}\text{C}$ and $^{16}\text{O}$ undergoing inelastic collisions with ambient H and He with sufficient energy ($\geq 20$ MeV/nucleon) to excite nuclear levels that decay via characteristic gamma line emission, substantially broadened (Kozlovsky, Ramaty & Lingenfelter, 1997). In this scenario the 0.5 - 1 keV X-ray emission from these regions could by dominated by somewhat broadened atomic K$\alpha$ lines associated with electron capture by fast C and O ions at $\beta \equiv v/c \leq 0.1$, mainly the 0.57 keV line from $\text{O}_{\text{VII}}$ and the 0.65 keV line from $\text{O}_{\text{VIII}}$ (Pravdo & Boldt, 1975; Tatischeff, Ramaty & Kozlovsky, 1998); sufficiently sensitive searches for this emission are yet to be made. Surveying the Milky Way for such X-ray lines would trace the location in our galactic neighborhood ($< 1$ kpc) of possible regions of enhanced subrelativistic cosmic rays.

What is the evidence for a significant interstellar population of subrelativistic ($\beta < 1$) cosmic ray nuclei broadly distributed throughout the galactic disk? Relative to the local interstellar flux of such nuclei beyond the heliosphere, the small flux arriving here at $\sim 1$ AU corresponds to severe attenuation by the solar wind. For a range of sufficiently low rigidities ($R$) the attenuation factor ($F$) may be approximated by

$$F \approx \exp(-K/\beta),$$

where $K \geq 1$, depending mainly on the overall spatial extent of the wind, its velocity and frozen-in magnetic field structure, but only weakly on $R$ (Parker, 1963). The upturn in the spectrum of subrelativistic nuclei observed below $\sim 20$ MeV/nucleon arises from an “anomalous” component now recognized as being energized within the heliosphere (Kinsey, 1970; Fisk, Kozlovsky & Ramaty, 1974; Jokipii & McDonald, 1995), thereby masking the identification of any subrelativistic interstellar cosmic rays with $\beta < 0.2$ that might arrive here at 1 AU. As here emphasized next, we can gain access to the illusive interstellar spectrum of subrelativistic cosmic rays by appropriate X-ray measurements that, in effect, provide the direct remote sensing of these particles called for.

Recent RXTE observations (Valinia & Marshall, 1998) of the apparently diffuse X-radiation (10→ 60 keV) from the galactic ridge [first observed in the 2 → 10 keV band by Bleach et al. (1972)] now indicate a non-thermal disk component having a
Is this luminosity providing us with a measure of the input required to produce the observed ionization of the ISM? To evaluate this we note that the intensity of the galactic Hα background measured at high galactic latitudes implies an average hydrogen recombination rate of \(4 \times 10^6 \text{s}^{-1}\) per cm\(^2\) of the galactic disk (Reynolds, 1984). With the required dissipation of \(\sim 40 \text{ eV}\) per electron-ion pair generated, the corresponding total galactic ionizing input \((Q)\) implied is

\[
Q = 7 \times 10^{41} \text{ ergs/s.} \quad (4)
\]

Taking \(L_x\) as the appropriate radiative measure of this total required rate of energy dissipation (i.e., the power input to produce the observed ionization) allows us to evaluate the associated radiative yield \((Y)\), viz:

\[
Y \equiv L_x/Q = 2 \times 10^{-4}. \quad (5)
\]

That the value of this radiative yield is comparable to what is expected for an energetic ionizing particle in the ISM with \(\beta \approx 0.2 - 0.5\), suggests that the observed 10-60 keV disk radiation arises mainly via the process of suprathermal proton (\& alpha) bremsstrahlung for a relatively high flux of cosmic ray particles at 20-120 MeV/nucleon (Boldt & Serlemitsos, 1969). The observed X-ray spectrum (eq. 2) then implies an interstellar cosmic ray spectral form for the particle flux given by

\[
\frac{\delta J}{\delta E} \propto E^{-1.3} \quad \text{(for } E = 20 - 120 \text{ MeV/nucleon).} \quad (6)
\]

For the particular band considered, this spectrum (eq. 6) is a remarkably good approximation to the similarly restricted portion of the interstellar cosmic ray spectrum proposed by Balasubrahmanyan et al. (1968). That spectral model corresponds to cosmic ray propagation through the ISM with an exponential distribution of path lengths having a mean value of 6 g/cm\(^2\) for injected particles whose spectra at the input sources exhibit a single power law that extrapolates from what is directly observed at \(E >> 1 \text{ GeV/nucleon}\) all the way down to \(E < 100 \text { MeV/nucleon.}\) As shown in that paper, comparing this interstellar spectrum with that observed, at solar minimum, implies that the modulation parameter for eq. 1 is \(K = 2.7\). Integrating the interstellar cosmic ray spectrum then yields a value for \(Q(> 20 \text{ MeV/nucleon})\) that is a substantial fraction of that required (eq.4) and an energy density of \(\sim 3 \text{ eV/cm}^3\), higher than previously considered (Gloeckler & Jokipii, 1967). If this conclusion is valid, then cosmic rays play a major (possibly dominant) role in the dynamics of the ISM. An alternate possibility that the power-law source spectra extrapolate to low energies on the basis of total energy (rather than kinetic
energy) would yield a cosmic ray flux whose energy density is only 0.6 eV/cm$^3$; however, the interstellar spectrum would then be incompatible with the observed X-ray spectrum and correspond to a $Q$ value two orders of magnitude too small. Confirmation of the RXTE result and this interpretation of it is clearly essential. The increased spatial resolution and bandwidth of the INTEGRAL spectrometer should provide the information needed to establish that the hard X-ray ridge emission is indeed mostly diffuse non-thermal radiation and give us precise maps of its surface brightness distribution that we can use to trace subrelativistic cosmic rays throughout the ISM of the Milky Way. Galactic ridge gamma-ray lines from excited states of interstellar $^{12}$C and $^{16}$O, those induced via inelastic collisions by cosmic ray particles, should further define the subrelativistic nucleonic component (Pohl, 1998). Although the volume emissivity of the galactic ridge in X-rays is more than an order of magnitude greater than that expected from the bremsstrahlung of cosmic ray electrons in the ISM, relativistic electrons could well account for most of the galactic bremsstrahlung emission in the 1-100 MeV gamma ray band (Strong et al. 1994).

4. FULL CIRCLE

In tabulating the estimated energy density in every radiation field of extrasolar origin that obtains here in our region of the Milky Way (outside the heliosphere) we note (see Table 4) that the galactic cosmic ray nucleonic component is the largest of all. The opposite extreme (at the bottom of the list), that of ultra-high energy extragalactic cosmic rays ($>10^{20}$ eV each), is manifested right here in the atmosphere of Earth at a rate somewhat less than one per km$^2$ per decade. This time using the atmosphere to good advantage (i.e., as a detection medium), Bird et al. (1995) have observed the atmospheric fluorescence produced by an extensive air shower initiated by a $3.2 \times 10^{20}$ eV ($\sim$50 Joule) cosmic hadron, the highest energy particle yet detected in nature. The Larmor radius for this energetic a proton in the galactic magnetic field would be $\sim 150$ kpc; in the intergalactic field it would be $\geq 300$ Mpc. Hence, such a particle must be extragalactic in origin. Furthermore, for a source distance much less than 300 Mpc its observed vector velocity would still be close to the initial direction of emission. However, due to collision losses with the 2.7$^\circ$ K background radiation field (Greisen, 1966; Zatsepen & Kuz'min, 1966), a proton this energetic could not have survived from a source more distant than 50 Mpc (Elbert & Sommers, 1995). And there are no suitable active galaxies in the right direction that are close enough to be viable source candidates. We emphasize here, however, that the present electromagnetic radiation field arising from accretion-driven AGNs in the past implies the existence of a substantial “local” population of apparently dormant galactic nuclei that harbor spinning supermassive black holes. These could be the sites of hidden dynamos sufficient for powering the required production of those cosmic rays whose energy is presently regarded as astrophysically excessive (Boldt & Ghosh 1998). Here, in this very extreme instance of high energy astrophysics, we again see the involvement of a profound cosmic
Table 4. Energy Density \([u \text{ (eV/cm}^3\text{)}]\) of Local Fields (outside heliosphere)

|   |                                                                 |     |
|---|-----------------------------------------------------------------|-----|
| 1 | Cosmic rays (\(> 20 \text{ MeV/nucleon}\))                     | \(\geq 1\) |
| 2 | Galactic magnetic field (\(B^2/8\pi\))                         | \(\sim 1\) |
| 3 | Starlight (galactic)                                           | 0.3  |
| 4 | 2.7\(^\circ\) K microwave background                           | 0.3  |
| 5 | 1.9\(^\circ\) K neutrino background                            | 0.1  |
| 6 | Cosmic ray electrons                                           | \(\leq 0.1\) |
| 7 | Extragalactic IR background (\(\lambda > 140 \mu\text{m}\))    | \(4 \times 10^{-3}\) |
| 8 | Extragalactic objects (\(\lambda = 0.36 - 2.2 \mu\text{m}\))  | \(3 \times 10^{-3}\) |
| 9 | Gravitational radiation background \([\nu(u_\nu)]\)             | \(\leq 6 \times 10^{-4}\) |
| 10| Quasar light (inferred bolometric)                             | \(3 \times 10^{-4}\) |
| 11| Cosmic (extragalactic) X-rays (\(> 1 \text{ keV}\))            | \(6 \times 10^{-5}\) |
| 12| Soft galactic X-rays (\(< 1 \text{ keV}\))                    | \(1 \times 10^{-5}\) |
| 13| Extragalactic (blazar) gamma-rays                              | \(9 \times 10^{-6}\) |
| 14| Galactic gamma rays (\(> 100 \text{ MeV}\))                   | \(8 \times 10^{-6}\) |
| 15| Galactic X-rays (\(> 1 \text{ keV}\))                         | \(6 \times 10^{-6}(2 \times 10^{-7} \text{ unresolved})\) |
| 16| Extragalactic cosmic rays (\(> 10^{20} \text{ eV}\))           | \(\sim 10^{-9}\) |

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ray/astronomy connection and the role of photons in revealing the origins of puzzling new exotic phenomena. We seem to have come full circle with this adventure. Our earth’s atmosphere, which initially was a seemingly insurmountable barrier for us in the detection of primary cosmic rays, is now the most effective detection medium available for the very highest energy quanta in nature. Although it would appear that the most energetic particles observed here must be produced in the present epoch of the universe, we look to the overall cosmic background of accretion-driven electromagnetic radiation for providing the integral measure, over all past epochs, that defines the local candidate source population of “hidden” supermassive black holes.

Even though local dormant quasar remnants are manifestly under-luminous, their underlying supermassive black holes are likely to be sufficiently spun-up [i.e., after their many “Salpeter” time units of accretion history (Thorne 1974; Rees 1997)] to possibly serve as high-energy accelerators of individual particles. In this scenario (cf., Blandford & Znajek 1977) externally produced magnetic field lines threading the event horizon of such black holes would, by virtue of the induced rotation, generate an effective electromotive force characterized by: \[ \text{emf} \propto cBR, \]
where \( B \) is the magnetic field strength and \( R \) is the effective range over which the concomitant electric field is applicable. Scaling to the magnitude for this impressed \( B \) field considered by Macdonald and Thorne (1982) and taking \( R \approx R_g(\equiv GM/c^2) \), the gravitational radius, the expected value for the \( \text{emf} \) is then here estimated as

\[ \text{emf} \approx 4 \times 10^{20} B_4 M_9 \text{ volts}, \]

where \( B_4 \equiv B/(10^4 \text{ Gauss}) \) and \( M_9 \equiv M/(10^9 M_\odot) \). We note that radiative losses for electrons in such a dynamo greatly exceed those for protons. Hence, radiative cascades (basic to the Blandford - Znajek mechanism), such as attend the process of electron acceleration, would not constitute a comparable limiting factor in the present scenario for the acceleration of the relatively few (favorably disposed) protons that need to achieve an energy close to that of exploiting the full voltage. The situation might well be one in which the accelerator is not operational in the mode in which quasi-steady conversion of the hole’s rotational energy into that of luminous radio jets is possible, but where acceleration of individual protons by it may occur, perhaps sporadically (Boldt & Ghosh 1998).

What are the environmental circumstances of the black hole nuclei in dormant quasar remnants and are they conducive to having sufficient accretion for sustaining the magnetic fields needed for this generator? The unusually low luminosities associated with the supermassive black holes at the centers of nearby bright elliptical galaxies (Loewenstein et al. 1998; Fabian & Rees 1995; Fabian & Canizares 1988) have been explained in terms of radiatively inefficient advection-dominated flow (Mahadevan 1997; Naranan 1997), even when there is ample ambient gas available for accretion. A recent critical reassessment (Ghosh & Abramowicz 1977) of the likely strengths of magnetic fields threading the horizons of accretion-disk fed black holes leads to the conclusion that these strengths are somewhat lower than
previously considered; considerations of advection-dominated disks as opposed to standard disks could further lower the estimated field strength. Taking $B_4 < 1$ in eq. 6 then implies that achieving the desired $emf$ would require $M_0 > 1$. What is the evidence for such supermassive black holes in a substantial present-epoch population of dormant galactic nuclei? In the nearby universe, there is a drastic paucity of quasars such as the extremely luminous ones ($L \geq 10^{47}$ ergs/s) evident at large redshifts ($z > 1$), those with putative black hole nuclei having masses $\geq 10^9 M_\odot$. Nevertheless, the local number of dead quasars associated with the same parent population (Schmidt 1978; Small & Blandford, 1992; Richstone et al., 1998) is expected to be relatively large. And now there is also direct stellar-kinematic evidence for individually identified massive dark objects (MDOs) at the centers of several nearby inactive galaxies (Kormendy & Richstone, 1992; Magorrian et al. 1998).

As emphasized by Soltan (1982) for a standard Friedmann cosmology, the total background radiation arising from the entire history of accretion fed AGN emission gives us a direct integral measure of the total mass built-up, that which is now present locally in the form of black holes in AGNs and their remnants. Independent of the Hubble constant ($H_0$) and deceleration parameter ($q_0$), the total mass density built-up by this accretion over all cosmic time ($t$) is given by

$$\rho(\text{growth}) = 2.6 \times 10^7 (\epsilon^{-1} - 1)(1 + \langle z \rangle)[u(eV/cm^3)] M_\odot/(Mpc)^3$$  (8a)

where:

$$\epsilon(\text{radiation efficiency}) \equiv L/[c^2(\delta M/\delta t)_{\text{accreted}}]$$  (8b)

$$u(\text{energy density}) \equiv 4\pi I/c = \int [(n(L))/(1 + z)] \delta t,$$  (8c)

$4\pi I$ is the omnidirectional bolometric background flux arising from AGNs, and $(n(L))$ is the comoving bolometric luminosity density.

Studies of the X-ray sky indicate a pronounced extragalactic cosmic X-ray background (CXB) that arises mainly from accretion powered AGN emission at previous epochs (Boldt 1987; Fabian & Barcons 1992). By correlating surface brightness fluctuations of the CXB with IRAS galaxies Barcons et al. (1995) find that the present-epoch 2-10 keV luminosity density is dominated by Seyfert 1 galaxies ($L_x > 10^{42}$ ergs/s). Padovani, Burg and Edelson (1990) have determined that the local mass density in the form of Seyfert 1 nuclei is $\sim 6 \times 10^2 M_\odot/(Mpc)^3$, half of which arises from black holes of mass $M > 3 \times 10^7 M_\odot$ and essentially none from any possible AGN black holes of mass $M > 2 \times 10^8 M_\odot$. For an accretion powered X-radiation efficiency $\leq 10\%$ (i.e., $\epsilon \leq 0.1$ in eq. 8a) the observed CXB energy flux implies the build-up of a local mass density $> 14 \times 10^3 (1 + \langle z \rangle) M_\odot/(Mpc)^3$, where $\langle z \rangle \geq 1$. This density is clearly much larger than that for Seyfert 1 nuclei. In order to account for the flux and spectrum of the CXB it is necessary to invoke a supplementary source population that somehow makes a substantial redshifted contribution to the observed CXB without making much of a contribution to the local 2-10 keV luminosity density (Boldt & Leiter 1995; Boyle et al. 1998). This needed
additional component (over and above that from Seyfert 1 nuclei) could arise from a population not at all represented locally [e.g., precursor AGNs necessarily at large z (Boldt & Leiter 1995)] and/or Seyfert 2 nuclei whose emission below $\sim 10$ keV is strongly attenuated by absorption (Madau, Ghisellini & Fabian 1994; Comastri et al. 1995). The unified Seyfert AGN model (Madau, Ghisellini & Fabian 1994) would imply that the present-epoch mass spectrum for Seyfert 2 nuclei would be the same as for Seyfert 1, renormalized by the ratio of their local number densities $\left(\frac{n_2}{n_1}\right)$. In particular, for these scenarios, using $\left(\frac{n_2}{n_1}\right) \leq 4$ (Madau, Ghisellini & Fabian 1994; Comastri et al. 1995) implies a total local Seyfert mass density $\leq 3 \times 10^7 M_\odot/(\text{Mpc})^3$, much less than that implied by the CXB flux. In these models, the bulk of the local mass density related to the CXB would be accounted for by dormant Seyfert remnants having the same average mass ($\sim 2 \times 10^7 M_\odot$) as the AGNs. Clearly, the black holes associated with Seyfert remnants are not massive enough to be viable candidates for the high energy dynamos we are looking for. The black holes associated with blazar remnants are likely to be appreciably more massive. If blazar emission is powered by accretion, then we can use eq. 8a, with the gamma-ray background energy density (Table 4), to evaluate that the local mass density in the form of associated black holes is $\geq 2 \times 10^3 (1 + \langle z \rangle) M_\odot/(\text{Mpc})^3$, where $\langle z \rangle \geq 1$ and $\epsilon \leq 0.1$; this blazar remnant density is somewhat larger than that associated with active (Seyfert) galaxies.

Considering a radiative efficiency of 10% for the accretion powered bolometric luminosity of quasars, Chokshi and Turner (1992) have calculated the mass built up over all earlier epochs and thereby estimated that the expected local mass density in compact galactic black hole nuclei is two orders of magnitude greater than that accounted for by Seyfert galaxies. They conclude that over 10% of this density is associated with black holes of mass $> 6 \times 10^8 h^{-2} M_\odot$, where $h = H_0/[100 \text{km s}^{-1} \text{(Mpc)}^{-1}]$. As emphasized by Chokshi and Turner (1992), the local universe is expected to be well populated by currently inactive remnants of quasars. Based on the mass function described by them we have estimated that, for $h \approx 0.5$, there should be about a dozen or more quasar remnant black holes of mass $> 10^9 M_\odot$ within 50 Mpc. These quasar remnant expectations are consistent with being lower limits to the number of corresponding supermassive black holes inferred from a recent comprehensive study of massive dark objects (MDOs) at the centers of 32 nearby galaxy bulges (Magorrian et al. 1998). In this connection we note that the number of MDOs within 50 Mpc identified in their sample as being more massive than $10^9 M_\odot$ is already 8, comparable to the total number of Seyfert 1 AGNs out to that distance. This is a lower limit to the total number of such supermassive MDOs within this volume since their sample of MDOs at the centers of nearby galaxy bulges is incomplete, albeit sufficiently large for the correlations sought by them (Magorrian 1998). Using the luminosity function for field galaxies (Efstathiou, Ellis & Peterson, 1988) to estimate the incompleteness of their sample suggests that the corrected number of supermassive MDOs could well be an order of magnitude greater than that so far observed. It is interesting to note that in their sample of 32 nearby MDOs (Magorrian et al. 1998) five are associated with
compact objects somewhat more massive than $10^{10} M_\odot$.

The sample of about 100 extraordinary cosmic ray events with energy $\geq 2 \times 10^{20}$ eV expected with the upcoming Auger extensive air-shower array (Cronin 1997) will come from nearby sources and, if protons, will point accurately to the directions of origin (i.e., owing to the correspondingly large particle Larmor radius in the weak intergalactic magnetic field). Candidate galaxies within the acceptable pixels would then be searched for stellar-dynamical evidence for central supermassive black hole nuclei [such as the MDOs discussed by Kormendy & Richstone (1995), Kormendy et al. (1997) and Magorrian et al. (1998)], here taken to be indicative of the dead quasar sources of the highest energy cosmic rays. If such a correlation is clearly established, and the lack of correlation with strong radio sources persists, it would imply that the existence of a black hole dynamo is not a sufficient condition for the presence of pronounced jets. The OWL (Orbiting Wide-angle Light-collectors) space borne NASA mission planned for observing, from above, those air showers induced by the highest energy cosmic rays is anticipated to have the sensitivity for accumulating an order of magnitude more such events than expected with the Auger array (Streitmatter 1998). If in fact no real correlation is found with sufficiently nearby MDOs, one would then have to pursue more exotic particle physics possibilities, disregarded in this present discussion, in which: 1) the primary hadronic particles are produced at ultra-high energies in the first instance, typically by quantum decay of some supermassive elementary particles related to grand unified theories (Sigl et al. 1995; Kuz'min and Tkachev 1998) or 2) a new neutral massive “S” hadron ($m_S c^2 > 2$ GeV) is produced whose energy loss to the cosmic microwave background is relatively small, even for very remote sources (e.g., quasars) at cosmological distances (Chung, Farrar & Kolb, 1998; Farrar & Biermann, 1998). If one of these new particle scenarios turns out to be the case, then cosmic ray research will have come full circle, back again to its role of providing the leading thrust towards new fundamental physics as well as astrophysics. “When we want to learn more about nature, exploration of extremes has consistently added to our knowledge and brought us surprises (Cronin, 1997)”

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