SLAC-PUB-10097
astro-ph/0303350

LABORATORY INVESTIGATIONS OF THE EXTREME UNIVERSE

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Recent years have seen tremendous progress in our understanding of the extreme universe, which in turn points to even deeper questions to be further addressed. History has shown that the symbiosis between direct observations and laboratory investigation is instrumental in the progress of astrophysics. Current frontier astrophysical phenomena related to particle astrophysics and cosmology typically involve one or more of the following conditions: (1) extremely high energy events;(2) very high density, high temperature processes; (3) super strong field environments. Laboratory experiments using high intensity lasers and particle beams can calibrate astrophysical observation or detection processes, investigate the underlying dynamics of astrophysical phenomena, and probe into fundamental physics in extreme limits. We give examples of possible laboratory experiments that investigate into the extreme universe.

INTRODUCTION

This is an exciting time for astrophysics and cosmology. New observations and results from space-based, ground-based, and underground-based experiments are pouring in by the day. These have presented great leaps in our knowledge of the universe, and experiments proposed for the years to come promise to further revolutionize our view. This frontier of science lies at the intersection among several sub-fields of physics. Specifically, there are fundamental issues that overlap astrophysics with particle physics, or that connect quarks with the cosmos. The study of which is called *particle astrophysics and cosmology* (See Fig. 1). The present state of pursuit in this frontier can perhaps be best summarized by the "Eleven Science Questions for the New Century" posted by the U.S. National Research Council's Committee on the Physics of the Universe (CPU)[1]. These are:

- **What is the dark matter?**
- **What is the nature of the dark energy?**
- **How did the universe begin?**
- **Did Einstein have the last word on gravity?**
- **What are the masses of the neutrinos, and how have they shaped the evolution of the universe?**
- **How do cosmic accelerators work and what are they accelerating?**
- **Are protons unstable?**
- **Are there new states of matter at exceedingly high density and temperature?**
- **Are there additional spacetime dimensions?**
- **How were the elements from iron to uranium made?**
- **Is a new theory of matter and light needed at the highest energies?**

There is also the astrophysical frontier that lies at the intersection between astrophysics and plasma physics (See also Fig. 1). It is known that the (ordinary) matter in our universe largely exists in the plasma state. While the study of *plasma astrophysics* has a long history, its modern frontier typically involves very high density, high pressure, and high temperature plasma processes. This frontier lies in the domain of the newly emerged field of *high energy-density physics*.

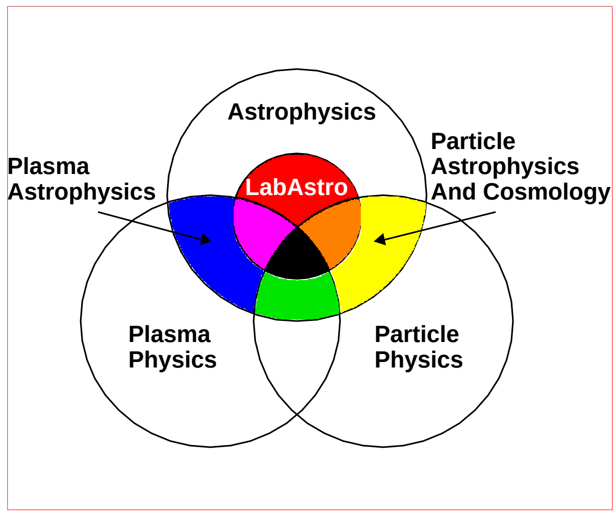

FIG. 1: A diagram that indicates the relationship between laboratory astrophysics and astrophysics, particle physics and plasma physics.

Astrophysical phenomena associated with the Eleven Science Questions raised above often involve one or more of the following extreme conditions:

- **Extremely high energy events, such as ultra high energy cosmic rays (UHECRs), neutrinos, gamma rays, etc;**
- **Very high density, high pressure, high temperature processes such as supernova explosions and gamma ray bursts (GRBs);**
- **Super strong field environments, such as that around black holes (BH) and neutron stars (NS).**

Due to these connections, certain aspects of the particle astrophysics issues are further linked with high energy-density physics (See Fig. 1).

Work supported in part by Department of Energy Contract DE-AC03-76SF00515

History has shown that the symbiosis between direct observations and laboratory investigations is instrumental to the progress of astrophysics. We believe that this will still be true in reaching ultimate answers to the above eleven science questions. Laboratory investigations of astrophysics have been very diverse, and the term "laboratory astrophysics" has been used in very different connotations. As the universe itself is a vast laboratory, almost every sub-field of physics finds its own connection to astrophysics, and thus its own associated laboratory investigations. This is true not only for particle physics and plasma physics, but also for nuclear, atomic, and molecular physics. In this article we focus on a subset of laboratory investigations that attempt to address certain aspects of the "eleven questions" in particle astrophysics and cosmology. Some of these involve only high energy processes or strong field environments, while some others are associated with high energy-density conditions (Again, see Fig. 1).

Many aspects of these extreme astrophysical phenomena, though not reproducible in the earth-bound laboratory, can be investigated by using the very high intensity photon and particle beams with the state-of-the-art technologies. The information so obtained can either be extrapolated to the actual astrophysical problems, or help to reveal their underlying physical mechanisms. Laboratory experiments can also help to characterize or calibrate astrophysical observations. Furthermore, the very complex astrophysical environments often render fully theoretical treatment impossible, and large scale computer simulations are indispensable. Yet limited by computer capacities and other constraints, even computer simulations require approximations and assumptions. Laboratory experiments can help to bench-mark the simulation codes and provide their validation. Finally, there also exists the possibility of using these technologies to probe into the unknown territory of physics at its very foundation. These different functions of laboratory investigations into the extreme universe can thus be largely classified into three categories. These are

1. Calibration of observation or detection processes;

2. Investigation of underlying dynamics;

3. Probing fundamental physics in extreme limits.

Laboratory calibration experiments aim at precision measurements for better determination of astrophysical observation or detection processes. The data acquired from such precision measurements can often stand-alone and may not require any extrapolation. Mundane as these experiments may be, their value for astrophysics is most certain.

Although it is possible using accelerator and laser technologies to create some energy, pressure or temperature conditions found in the cosmic sources, it is clear that laboratory conditions would never reproduce the astrophysical environments completely. Thus the value of the part of experiments that investigate the underlying dynamics of astrophysical phenomena lies not in recreating the astrophysical environments per se, but in determining the physical mechanisms in a generalizable, device-independent fashion so as to extrapolate or export our understanding, for example by means of computer simulations, to these extreme astrophysical conditions.

Experiments that aim at discovery of fundamental physics in its extreme limits, though exciting, are the least assured among the three categories. The underlying physical principles, such as the quantum nature of the spacetime, are still vague. In addition, the extreme physical conditions to be probed often render the signatures extremely faint. These imposes severe challenges to this line of effort. Nevertheless, given the potential scientific return, it would seem short-sighted if these efforts are categorically dismissed.

UNIVERSE AS A LABORATORY

Our Universe is a vast laboratory which produces physical phenomena in their most extreme conditions. Here we give a few examples.

Extremely High Energy Events

Dictated by the inevitable interaction between the UHE proton and the cosmic microwave background radiation, Greisen[2] and Zatsepin and Kuzmin [3] showed that protons with initial energy $\geq 5 \times 10^{19}$eV originated from a distance larger than ~ 50 Mps cannot survive to the earth. Yet UHECR with energies above the GZK cutoff have been found in recent years [4, 5, 6, 7] without identifiable local sources. Observations also indicate a change of the power-law index in the UHECR spectrum (events/energy/area/time), $f(\epsilon) \propto \epsilon^{-\alpha}$, from $\alpha \sim 3$ to a smaller value at energy around $10^{18} - 10^{19}$eV (See Fig. 2).

So far the theories that attempt to explain the UHECR can be largely categorized into the "top-down" and the "bottom-up" scenarios. The top-down scenario assumes that the UHECRs are originated from the decay of extremely heavy fundamental particles, while the bottom-up scenario assumes that these are ordinary particles (e.g., protons) that have been accelerated to extremely high energies. In addition to relying on exotic particle physics beyond the standard model, the main challenges of top-down scenarios are their difficulty in compliance with the observed event rate and the energy spectrum [8], and the fine-tuning of particle lifetimes. The main challenges of the bottom-up scenarios, on the other hand, are the GZK cutoff, as well as the lack of an efficient acceleration mechanism [8]. To circumvent the GZK limit, several authors propose the "Z-burst" scenario [9, 10] where

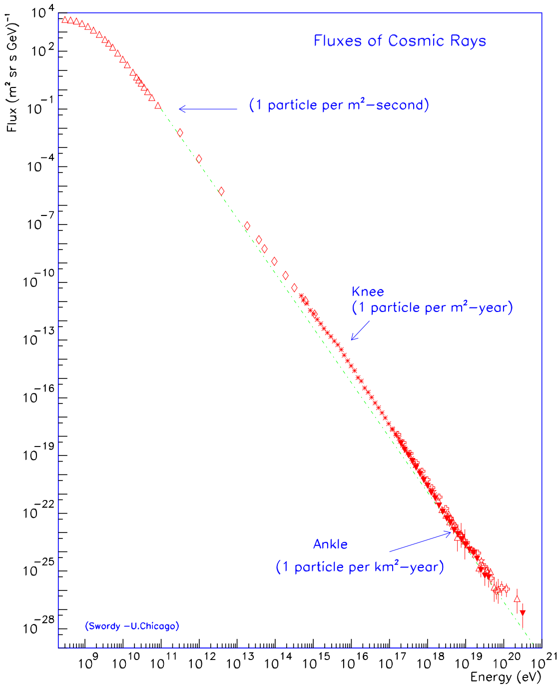

FIG. 2: Ultra high energy cosmic ray flux as a function of energy.

neutrinos, instead of protons, are the actual messenger across the cosmos.

Even if the GZK-limit can be circumvented through the Z-burst scenario, the challenge for a viable acceleration mechanism remains acute. The existing paradigm for cosmic acceleration, namely the Fermi mechanism [11] (including the diffusive shock acceleration [12, 13, 14, 15]), is not effective in reaching ultra high energies. These acceleration mechanisms rely on the random collisions of the high energy particle against magnetic field domains or the shock media, which necessarily induce increasingly more severe energy losses at higher particle energies. Are there alternatives, and how can we verify them?

Ultra High Energy-Density Processes

GRBs are by far the most violent release of energy in the universe, second only to the big bang itself. Within seconds (for short bursts) about $\epsilon_{\rm GRB} \sim 10^{52}$erg of energy is released through gamma rays with a spectrum that peaks around several hundred keV. Existing models for GRB, such as the relativistic fireball model [16], typically assume either neutron-star-neutron-star (NS-NS) coalescence or super-massive star collapse as the progenitor. The latter has been identified as the origin for the long burst GRBs (with time duration $\sim 10 - 100$ sec.) by recent observations [17, 18]. The origin of the short burst GRBs, however, is still uncertain, and NS-NS coallescence remains a viable candidate. Even if the progenitors are identified, many critical issues remain to be addressed. What is its underlying dynamics? Figure 3 shows a schematic diagram that depicts a recent model[19], which extends from the "relativistic fireball model". While both models assume the outburst of a relativistic fireball, the new model further assumes a high temperature quark-gluon plasma exploding from the NS-NS epicenter outward as its origin. Is this notion correct? Are there ways to test the assumptions invoked by different GRB models?

FIG. 3: A model for gamma ray burst. It assumes that the outbursting fireball undergoes three physical stages, described as the *hadrosphere, leptosphere, and plasmosphere.*

Super Strong Field Environments

In the vicinity of compact objects such as neutron star and black hole, the electromagnetic as well as gravitational fields are believed to be extremely intense. For example the magnetic fields around a neutron star is approaching the Schwinger critical field strength, i.e., $\sim 4 \times 10^{13}$G, while the gravitational collapse of a super massive star to a charged black hole may generate an electric field that is comparably intense. In addition, gravity near the event horizon of a black hole is so strong that general relativity has to be invoked in order to properly describe its dynamics.

Furthermore, under such super-strong fields quantum effects play essential roles. For example under the Schwinger critical field condition the QED vacuum becomes unstable and e^+e^- pairs can be copiously created spontaneously. Black holes, on the other hand, can provide a fertile test bed for the eventual understanding of quantum gravity, for example, via Hawking radiation [20]. Can any of these be tested in the laboratory setting?

Extreme Limits of Spacetime and Vacuum

Understanding the nature of the physical vacuum has been a perpetual challenge in physics, from the concept of aether in the 19th century to the notion of "dark energy" into this new century, which is considered to have contributed about 2/3 of the present energy density of our universe. What is dark energy? Some believe that the answer to it relies on the ultimate development of a theory that unifies quantum mechanics and Einstein's general theory of relativity. While such an ultimate theory is still lacking, certain feature of a quantum theory

FIG. 4: Quantum fluctuations of spacetime at the Planck scale.

FIG. 5: A schematic diagram of two basic schemes for UHECR detections. AGASA relies on a ground array of Cherenkov tanks to measure the lateral shower profile, while HiRes uses a Fly's Eye (or two) to receive shower-induced fluorescence from the atmosphere.

FIG. 6: Comparison of the UHECR energy spectra measured by HiRes and AGASA

of gravity appears inevitable. In particular quantum effects of gravity should be non-negligible, or vise versa the spacetime should become foamy or granular, at around the Planck mass, $M_p = (\hbar c/G)^{1/2} \approx 1.2 \times 10^{19}$GeV, or the Planck distance, $l_p = (G\hbar/c^3)^{1/2} \approx 1.6 \times 1^{-33}$cm. Probing the nature of vacuum and the granularity of spacetime at such an extremely high energy or short distance scale is clearly beyond any earth-bound extrapolation. Did Einstein have the last word on gravity? Are we truly out of hope to probe this ultimate energy limit?

LABORATORY STUDIES OF THE UNIVERSE

Existing technologies can produce high energy particle beams and laser beams with intensities at or above 10^{22} Watt/cm^2 at sufficiently high repetition rates. Such high intensity of EM energy can couple efficiently with air molecules, plasmas or solid material. These can be used, for example, to calibrate air fluorescence induced by cosmic ray showers, or to investigate the underlying acceleration mechanism that produces ultra high energy cosmic rays. High intensity lasers can impinge on thin solid films to create conditions similar to supernova explosions. Relativistic e^+e^- plasma jet can be produced by either converging two e^+ and e^- beams or by laser-induced pair production. The e^+e^- jet can further interact with stationary plasma or other material to simulate astrophysical jet environments. In addition, high energy, high intensity electron beams can be efficiently converted to high fluence photon beams (tunable from x-ray to gamma-ray) by either colliding with laser pulses or channeling through an undulator or a crystal. These intense bursts of radiation throughout the spectrum can mimic those thought to operate in astrophysical environments.

As stated in the Introduction, laboratory investigations into the extreme universe can be largely classified into three categories. These are 1. Calibration of observation or detection processes; 2. Investigation of underlying dynamics; and 3. Probing fundamental physics in extreme limits. We provide examples of existing or possible experiments in each of these categories.

Calibration of Observation or Detection Processes

Experiments in this category often do not invoke high density or high pressure settings. Instead they look for precision measurements of physical processes that are involved in astrophysical observations. Here we give a few examples.

Fluorescence in Air from Showers

There currently exist two different experimental techniques in the detection of UHECR. These are the air fluorescence technique, employed by the HiRes experiment [6], and the ground array detection employed by the AGASA experiment [5] (see Fig. 5). Both HiRes and AGASA have observed ultra high energy events above the GZK-cutoff. These two experiments, however, disagree in absolute flux of UHECR as well as in the shape of the UHECR energy spectrum. The HiRes UHECR flux measurement is systematically smaller than the AGASA measurement. The kink in the HiRes spectrum around 30 EeV may indicate a pile-up due to the GZK effect, or the appearance of a new extra-galactic component. This kink is not observed at this energy by AGASA. This existing discrepancy (See Fig. 6) between HiRes and AGASA still lacks a resolution.

For ground-based as well as the future space-based observations, energy estimation of an extensive air shower depends on an accurate knowledge of atmospheric fluorescence efficiency. Air fluorescence is a useful tool for cosmic ray measurements because its emission spectrum is in the near-ultraviolet (300–400 nm) where the atmosphere exhibits almost no absorption and a relatively long scattering length (10–20 km) and because the yield (in photons per meter per electron) is virtually independent of altitude up to about 15 km.

High energy electron beams are ideal for such a study for the following reasons:

A. An extensive air shower produced by a hadron at relevant cosmic-ray energies is a superposition of electromagnetic sub-showers. Most of the shower energy at shower maximum is carried by electrons near the critical energy of air (100 MeV). The atmospheric fluorescence energy measurement is dominated by the luminosity of the shower at its maximum development.

B. Important N_2 fluorescence transitions (upper levels of the Nitrogen 2P system) are not accessible by proton excitation. Electron beams are required to study all the relevant transitions.

C. The energy distribution of electrons in the resulting shower as it exits the target into a controlled atmosphere is calculable and similar to what is expected in a UHE shower near shower maximum. Incidentally, a 10 GeV electron beam with 10^{10} particles carries a total energy $\sim 10^{20}$ eV, the same order of magnitude as UHECR.

The superposition of showers produced by a high energy beam can be modeled by softwares and the fluorescence yield can be measured at various stages of the shower development, allowing detailed comparison with Monte Carlo simulations. A proposal by an international collaboration[21] to do such an experiment on "Fluorescence in Air from Showers" (FLASH) at the Stanford Linear Accelerator Center has recently been approved. More details can be found in the companion article by P. Sokolsky in this volume. We expect that in about one year, this experiment should help to partially resolve the discrepancy between HiRes and AGASA, and would provide reliable and much needed shower data for future fluorescence-based UHECR experiments.

Neutrino Astrophysics and Askaryan Effect

Another good example of calibration experiments is the recent observation of the Askaryan effect[22]. During the development of a high-energy electromagnetic cascade in normal matter, photon and electron scattering processes pull electrons from the surrounding material into the shower. In addition, positrons in the shower annihilate in flight. The combination of these processes should lead to a net 20-30% negative charge excess for the comoving compact body of particles that carry most of the shower energy. G. A. Askaryan[23] first described this effect, and noted that it should lead to strong coherent radio and microwave Cherenkov emission for showers that propagate within a dielectric.

The observation of this effect should provide strong support for experiments designed to detect high energy cosmic rays and neutrinos via coherent radio emission from their cascades.

Heavy Element X-Ray Spectroscopy

One approach toward an answer to one of the "eleven questions", "Did Einstein have the last word on gravity?", is through x-ray probes of strong gravity[24]. It is suggested that x-ray observations will allow us to probe the spacetimes of black holes *in detail*. There exist three "lucky breaks" of black hole accretion that help to make such a claim possible. 1. (Many) accretion flows are "cold"; 2. Accretion disks are not fully ionized; 3. Accretion disks are illuminated by flaring coronae. These flares exicte different regions of disk at different times. By watching evolving echoes of flares one can map different slices of spacetime. As heavy elements, such as iron, in the disk are not fully ionized, their spectral lines are excited by the x-ray irradiation from the disk corona, and the reflected x-rays would be imprinted with iron lines (see Fig. 7). However, the x-ray spectroscopy, including its polarization property, in this regime has not been well measured. It has been suggested[24] that laboratory experiments using high intensity x-rays to measure heavy ion atomic transitions could be very valuable in this effort.

Investigation of Underlying Dynamics

This category of experiments aims at resolving the dynamical underpinnings of certain astrophysical phenomena under extreme conditions. Such phenomena often involve high energy-density environments, which may or may not overlap with extremely "high energy" processes.

Cosmic Acceleration Experiments

In addition to the first order (diffusive shock) and second order Fermi accelerations, there exist other interesting proposals, such as the idea of "Zevatron" [25]. Another cosmic acceleration mechanism was recently introduced [26], which is based on the wakefields excited by the Alfven shocks in a relativistically flowing plasma.

In the cosmic plasma wakefield acceleration model, there exists a threshold condition for transparency below which the accelerating particle is collision-free and suffers little energy loss in the plasma medium. The stochastic encounters of the random accelerating-decelerating phases results in a power-law UHECR energy spectrum: $f(\epsilon) \propto 1/\epsilon^2$. By invoking GRB atmosphere as the site for such an acceleration (see Fig. 3), protons with energies much beyond the GZK-limit can be produced. When the Z-burst scenario is further invoked, the estimated event rate in this model agrees with that from UHECR observations.

To test this mechanism, one can envision a setup where a e^+ beam and a e^- beam converge into a relativistic "plasma". Alfven shocks can be excited by sending this "plasma" through the superposition of a solenoid field and an undulator field (see Fig. 8). Plasma wakefields so excited will randomly accelerate or decelerate beam particles, resulting in a power-law energy spectrum. The acceleration gradient observed can then be extrapolated to and confronted against the astrophysical conditions. The diffusive shock acceleration can in principle also be investigated using such a relativistic plasma.

FIG. 7: A schematic diagram of BH acretion disk and x-ray emissions.

FIG. 8: A conceptual design of an experiment to test the principle of Alfven-wave induced plasma wakefield acceleration mechanism for UHECR.

FIG. 9: Simulations of relativistic jet induced shock wave[27].

Relativistic Jet Dynamics Experiment

Highly energetic and collimated astrophysical jets emitted from galactic centers and AGNs are common feature in our universe. How are they created? How do they interact with their environments? These jets often propagate over distances that are orders of magnitude larger than their sources and are still extremely confined. Why are they so collimated?

Computer simulations using magnetohydrodynamics (MHD) or particle-in-cell approach can address certain aspects of these issues (See Fig. 9). However typical simulations are highly idealized and are carried out in low dimensions. Based on the similar concept described in the cosmic acceleration experiment, e^+e^- beams can be merged to simulate a relativistic astrophysical jet. By sending such a jet through a stationary plasma or solid environment the dynamics of jet propagation can hopefully be better studied[28]. This can then help to benchmark the computer codes.

Probing Fundamental Physics in Extreme Limits

Event Horizon Experiment

The celebrated Hawking effect [20] suggests that BH is not entirely black, but emits a blackbody radiation with temperature $kT_H = \hbar g/2\pi c$, where g is the gravitational acceleration at the BH event horizon. Unfortunately the Hawking radiation for a typical astrophysical BH is too faint for observation. Through the Equivalence Principle there exists a similar effect, the Unruh effect [29], for a "particle detector" undergoing uniform acceleration. The accelerating detector would find itself surrounded by a heat bath with temperature $kT_U = \hbar a/2\pi c$, where a is the proper acceleration of the particle (see Fig 10). This very fundamental Hawking-Unruh effect can in principle be investigated via extremely violent acceleration provided by a standing-wave of ultra-intense lasers [30]. Through this, the nature of the "event horizon" can hopefully be better understood. An experimental concept for detecting the Unruh effect is shown in Figure 11.

FIG. 10: Analogy between Hawking and Unruh effects.

FIG. 11: A conceptual design of an experiment for detecting the Unruh effect.

Probing Spacetime Granularity

It is generally agreed that the spacetime at the Planck scale is topologically nontrivial, manifesting a granulated structure, or "quantum foam". Quantum decoherence puts limits on spacetime fluctuations at Planck scale, and semi-classical quantum gravity and string theory support the idea of loss of quantum coherence at the Planck scale. But how can one ever probe this property at the extremely minute Planck scale?

In Einstein's seminal paper (1905) on Brownian motion, the microscopic properties of atoms could be inferred by observing stochastic fluctuations of macrostructures. In a spirit analogous to Einstein's, Power and Percival[31] suggested that Planck scale spacetime fluctuations can induce stochastic phase shifts, and therefore the diffusion of the wave function. This effect can in principle produce decoherence in a atom interferometer (See Fig. 12). Rutherford Appleton Lab in the U.K. is currently considering such an experiment[32].

SUMMARY

As a sub-discipline of astrophysics, laboratory astrophysics spans across a broad spectrum of activities. In this article we focus on a subset of it that aims at addressing outstanding questions facing particle astrophysics and cosmology today, where certain aspects overlap with plasma astrophysics, or high energy-density physics. We classify laboratory astrophysics experiments into three categories, and discuss the promises and challenges in each of them. The eleven questions are deep and fundamental, and one should not expect easy answers to them. Direct space-based, ground-based, and underground-based observations or experiments are irreplacible in reaching the extreme universe. But we believe vigorous laboratory investigations would greatly enhance our ability in finding the ultimate answers.

This work is supported by Department of Energy under contract DE-AC03-76SF00515. We are grateful for the assistance of Kevin Reil in preparing this paper.

FIG. 12: Probing spacetime granularity at Planck scale with atom interferometry.

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[33] P. Chen, VERSIONS OF THIS PAPER WITH ALL FIGURES CAN BE FOUND AT www.slac.stanford.edu/grp/ara/labastro/AAPPS_a.ps or AAPPS_a_bw.ps.