NASA-CR-204041

FINAL REPORT

"Cosmic Ray Air Shower Measurement From Space"

NAS 8-38609 D.O. 161 (1/18/96 - 11/17/96)

Principal Investigator:

Yoshiyuki Takahashi

Department of Physics, OB 212
University Alabama in Huntsville, Huntsville, AL 35899

TEL: (205)890-6276 ext 212, FAX: (205)890-6873

ABSTRACT

A feasibility study has been initiated to observe from space the highest energy cosmic rays above 10^{20} eV. A satellite observatory concept, the Maximum-energy Auger (Air)-Shower Satellite (MASS), is recently renamed as the Orbital Wide-angle Collector (OWL) by taking its unique feature of using a very wide field-of-view (FOV) optics. A huge array of imaging devices (about 10^6 pixels) is required to detect and record fluorescent light profiles of cosmic ray cascades in the atmosphere. The FOV of MASS could extend to as large as about 60° diameter, which views $(500 - 1000\ \text{km})^2$ of earth's surface and more than 300 - 1000 cosmic ray events per year could be observed above 10^{20} eV. From far above the atmosphere, the MASS/OWL satellite should be capable of observing events at all angles including near horizontal tracks, and would have considerable aperture for high energy photon and neutrino observation. With a large aperture and the spatial and temporal resolution, MASS could determine the energy spectrum, the mass composition, and arrival anisotropy of cosmic rays from 10^{20} eV to 10^{22} eV; a region hitherto not explored by ground-based detectors such as the Fly's Eye and air-shower arrays. MASS/OWL's ability to identify cosmic neutrinos and gamma rays may help providing evidence for the theory which attributes the above cut-off cosmic ray flux to the decay of topological defects. Very wide FOV optics system of MASS/OWL with a large array of imaging device is applicable to observe other atmospheric phenomena including upper atmospheric lightening. The wide FOV MASS optics being developed can also improve ground-based gamma-ray observatories by allowing simultaneous observation of many gamma ray sources located at different constellations.

1. INTRODUCTION

The eventual study of the highest energy cosmic rays beyond 10^{20} eV began in early 60's by discovery of the first-generation events by Linsley et al.[1] Further study, however, has been a speculated issue for decades (**Fig. 1**), particularly considering the energy loss processes ($p\gamma$) of the Greisen-Zatsepin-Kuzmin (GZK) effect[2] for far-distant, extra-galactic sources of protons and nuclei. A more direct question is, "what is the maximum cosmic ray energy, if there is any limit?".

Acceleration mechanisms to the maximum air shower energies have long been an unsolved mystery in cosmic ray and high energy astrophysics. Furthermore, there are significant, recent questions. The highest energy cosmic rays are at energies only a few decades below the Grand-Unification Energy (10^{24-25} eV), though still far from the Planck Mass regime of > 10^{28} eV. Topological defects of the quantum vacuum in the Big-Bang or in the local cosmos were discussed by Schramm, Bhattacharjee and others, in which cosmic strings played an essential role for releasing X-bosons ($m_X \approx 10^{24}$ eV) that would emit the highest energy quarks and leptons as decay products.[3] In this sense, the decay of very massive, unified X-particles could shed light on the mystery of particles of unlikely energy arriving at earth. A new interest consequently grew in the highest energy neutrinos[6] and gamma rays with energies beyond 10^{20} eV that might possibly originate from topological defects. Active Galactic Nuclei (AGN), and other, possible origins of hadronic cosmic rays above 10^{20} eV within 100 Mpc have also stimulated interests in the directional information for these particles, which may lie in the super-galactic plane.[4]

The most straightforward detector concept is, of course, an extension of conventional, ground-based array of scintillators.[1] Most recent idea is the Auger Laboratory[4] with water Cherenkov tanks. The size of such an array is practically limited to less than (100 km)^2, and the maximum energy is limited by the expected flux to 10^{21} eV.[4] Other approaches were proposed in the past, which included global radio monitoring and space-based [5] observations. The former has been plagued by formidable background uncertainties. The latter concept of a satellite observatory was first proposed by Linsley in 1979, but it was not readily feasible with the optics and imaging technology at the time. The state of space technology and interests in the highest energy cosmic rays at that time were not sufficient to push Linsley's pioneering ideas. Recently, this idea was rejuvenated and updated by Takahashi.[6] With the advent of a large-aperture wide Field-of-View space optics[7] and fast imaging data analysis technology, it now appears feasible for observation of giant air showers from space.

The basis of the observation is fluorescent light emission from atmospheric nitrogen molecules excited by air shower electrons.[8] A high energy air shower forms a significant streak of scintillation light over 10 - 100 km along its passage in the atmosphere (depending on the energy and angle). This Greisen-Bunner and Suga signal [8] was first explored by "fly's eye" experiments at Cornell [8] more than 30 years ago, and Tanahashi et al.[9] finally succeeded in 1968 to detect the air shower fluorescence signals. This optical air shower detector has been successfully implemented on ground by Utah's Fly's Eye for the past 15 years.[10]

A "quantum leap" has been made in the last decade in imaging technology, high-density data transfer and efficient fast electronic devices. Space platform observations already succeeded in imaging the sky for upper-atmospheric lightning studies.[11] They used a 1 ~ 2 msec CCD readout with an automatic background subtraction algorithm, which successfully observed lightening even in high-backgrounds of daylight sky (**Fig. 2**). The possibility to observe large air showers from a satellite has become more realistic with recent development of wide field-of-view (FOV) optics for space applications.[7] Such innovative optics has been developed at the University of Alabama in Huntsville for application to the Ultraviolet Imager (UVI) instrument (triple mirrors),[12] and a new concept for the MASS (multiple lenses and/or catadioptric system).[7]

A future mission, Maximum-energy Auger-Shower Satellite (MASS: **Fig. 3**), could use these new technologies to survey a field-of-view of ~ 1,000 km x 1,000 km, making the exposure factor sufficient to reach 10^{22} eV, and eventually, beyond. A proposal with the title "Orbital Wide-angle Light-collector (OWL)", recently evolved from the MASS initiative, was selected at NASA for Advanced Mission Concept Study (PI: J. F. Ormes).

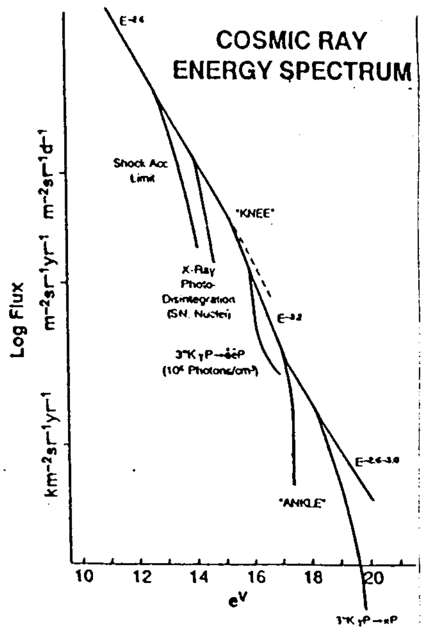

Fig. 1 Conceptual cut-offs of cosmic ray energy spectrum up to GZK effect.

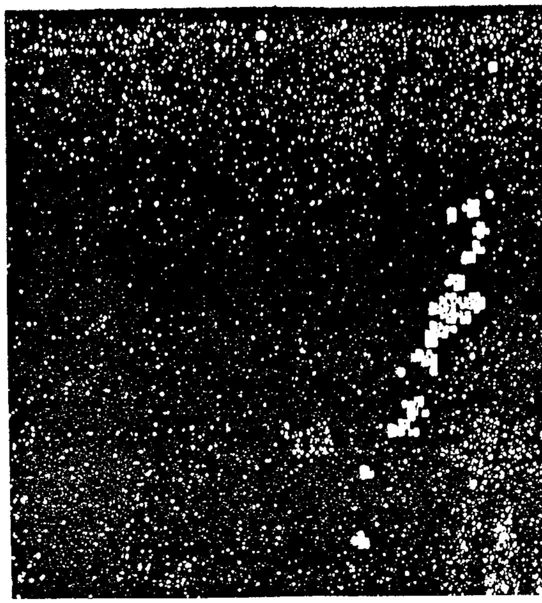

Fig. 2. CCD view of oceanic lightning, west of Hawaii on 13 April, 1995.[11]

2. HIGHEST ENERGY NEUTRINOS FOR STANDARD AND UNIFICATION THEORIES

AGN's are generally suspect for acceleration of very high energy cosmic rays. Their jets are known to have electron beams with Lorentz boosts of at least 10 (or in some analysis, up to ~ 10^4). Enhanced shock acceleration to that degree over the ordinary interstellar shock acceleration limit may be possible in AGN's jets. However, it still is not clear if the AGN can really accelerate protons and nuclei to energies beyond 10^{20} eV without being prevented by rapid energy loss in interactions with intense in-situ x-rays, optical and infrared photons. On the other hand, if the maximum-energy cosmic rays are decay products of topological defects and originate from distant space (> 100 Mpc), a large amount of neutrinos and photons are expected at earth up to energies of 10^{24} eV and some protons (up to ~ 10^{22} eV).

MASS/OWL is particularly sensitive to neutrinos at all angles, because transparent, fiducial target of > 10^{13} tons are available for interaction. If the highest energy showers are initiated by neutrinos, they would clearly appear at large zenith angles and at large atmospheric depths where no ordinary hadron-initiated showers exist, and the neutrino cross section for these energies could be learned from the angular and energy dependence of their showers.

The neutrino cross section in the ancient weak theory increases at very low energies, $\sigma \propto E_\nu$, and then becomes constant at CMS energies beyond the W-boson mass ($M_W \sim 10^{11}$ eV). An increasing cross section beyond $E_{cms} \sim M_W$ is obvious in the Standard Theory of QCD due to the increasing number of partons up to the unified mass M_x (~ 10^{24} eV), showing a significant energy dependence (F. Halzen et al., Quigg et al,[13] **Fig. 5**). The theoretical cross section,

$$\ln \sigma \propto 2\sqrt{\ln E_\nu}$$

can be approximated by $\sigma \propto \sqrt{E_\nu}$. It is > 0.1 μb at 10^{21} eV for neutrino-nucleon and > 1.4 μb for neutrino-Air interactions, much larger than the pre-Standard Model asymptotic value above $E_{cms} \sim M_W$, which enhances the frequency of large angle air showers. Possible effects of Grand Unified Theory (GUT) can be discussed when the observable energy (E_ν) goes beyond 10^{21} eV and detection of both neutrinos and photons could be made.

If AS observations fail to confirm the GZK effect above 5×10^{19} eV for protons, either the proton sources are within ~ 10 Mpc or the special relativity fails at above Lorentz factor ($\gamma > 10^{10}$).[14] An exotic, but fundamental, cosmological interest for high energy interactions[14] exists with high energy neutrinos in this context. Extremely high energy neutrinos above 10^{20} eV are extremely high Lorentz factor particles. Any possible "rest system" of the universe that would allow velocity addition could prevent [14] interactions along the "rest system vector" when the velocity sum could exceed light velocity (cf., Michelson-Morley experiment). If we accept a recent belief of the finite mass of light neutrinos as $m_\nu \leq 1$ eV, EHECR neutrinos would be the highest Lorentz factor known to us (in the order of $\gamma \geq 10^{20}$). The special relativity could be examined to the highest degree by looking for a line of the void vector for the anisotropy of neutrino events. The "rest-system" of the universe, if any exists, could be examined to the finest degree of $v \leq 10^{-10}$ cm/s. $1,5 \times 10^{-30}$

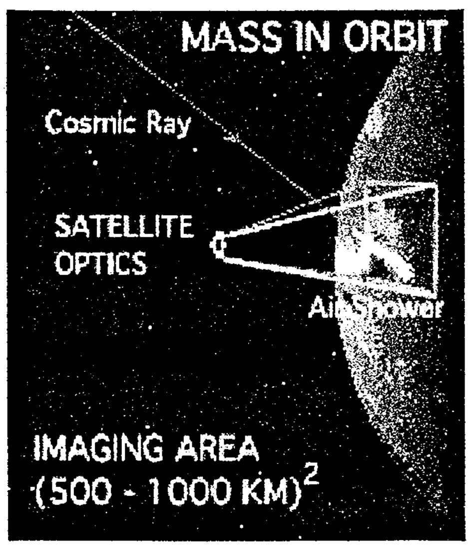

Fig. 3 Artist view of the MASS on orbit.

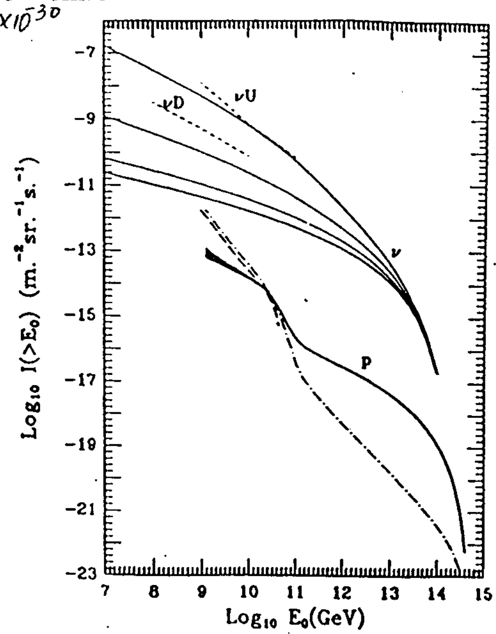

Fig. 4 Neutrinos from topological defects (by Bhattacharjee).[15]

The conventional estimate of the highest-energy neutrino events is not very large even with MASS. The flux would be at the level of 1 event per day and the number of observable events would be several events per year or less, even if we take account of all the known sources such as photo-production and 3°K background collisions with protons (Sato et al.,[16] **Fig. 6**). Atmospheric neutrinos are negligible.[17] However, topological defects model predicts 1 ~ 10 events per day with MASS. If such high rate of neutrino events are indeed found*and* no vertical, upward-going showers are seen, such observation could become a highest-energy proof for the Standard Theory as well as critical evidence for topological defects (Bhattacharjee,[15] **Fig. 4**) of the inflationary universe models.

The flatter air shower spectrum observed above 10^{18} eV ("Ankle"; changing from $E^{-3.0}$ to $E^{-2.7}$) has been considered as evidence for an extragalactic origin. The increasing observability of neutrinos under the Standard Theory scheme would make the observable spectrum of this component flatter by

$E^{0.32 \sim 0.5}$ relative to the already flatter spectrum of (presumably) hadrons at above 10^{19} eV. Neutrinos may dominate observations at the highest energies, although their possible generation is still speculative.

A satellite view is most effective for horizontal air showers, unlike the Fly's Eye or ground air shower arrays. A long streak of light would be seen across the image-plane of MASS. It is recognized that if high-resolution CCD imaging is feasible, a single "snapshot" alone (projected shower profile without temporal differentiation of pixels) would allow determination of the energy, the zenith angle and the altitude of the shower maximum to a certain degree of resolution. Two units of MASS, stereo-satellites, with fast time resolution imaging devices (e.g., PMT's) at each pixel would be required for the maximum information on the shower development. Optimization of these two different configuration will require careful examination, considering the required spatial and temporal resolution.

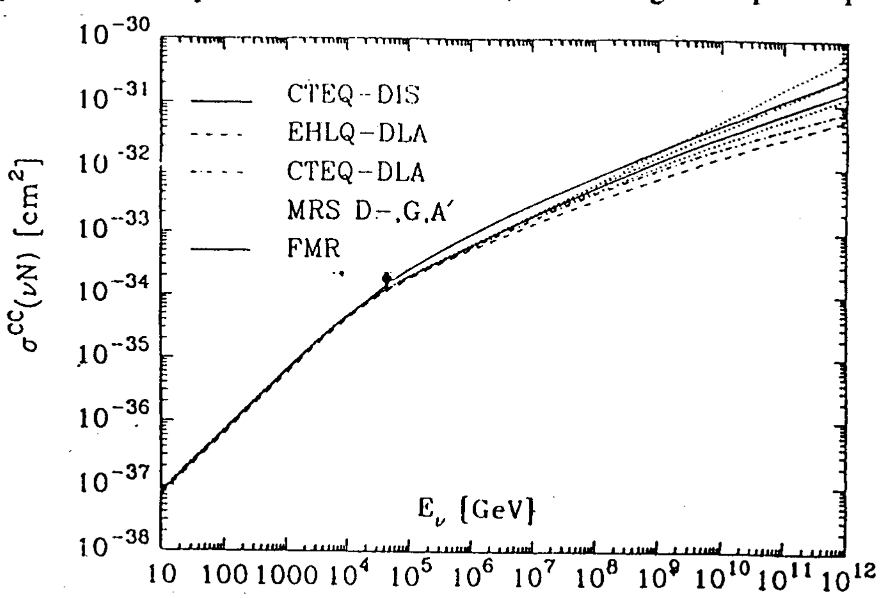

Fig. 5 Increasing neutrino cross section (Halzen et al.[13]). Curves are for different structure functions

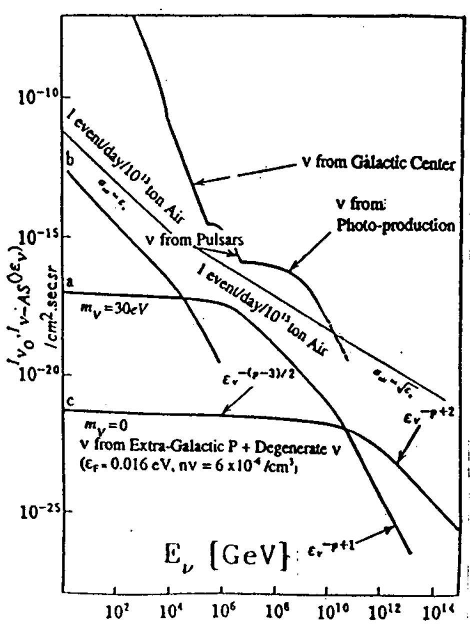

Fig. 6 Neutrino energy spectrum without topological defects (after Hara and Sato[16]).

3. CONCEPT OF INSTRUMENTS

The MASS/OWL must observe a large area of earth surface (500 ~ 1,000 km)^2. Considering the required accuracy of track analysis and signal strength, imaging of $\leq \sim (1\ \text{km})^2$ of earth's atmosphere should be a single pixel of 1 micro-steradian (or 3.4 ~ 6.8 arcmin; 0.06° ~ 0.12°). Below we discuss the case of the 1000 km orbit for observing the area of (1000 km)^2.

The shower maximum of a 10^{20} eV air shower contains ~ 6 x 10^{10} electrons, and each electron produces approximately 1 scintillation UV photon from 20 cm of track length in the air. The single pixel at shower maximum will deliver photons to 1,000 km altitude orbit on the order of 40 photons/m^2, if an air shower with zenith angle 45° is assumed. A large aperture ($\geq$ several m^2) is needed for the MASS optics to collect a sufficient number of UV photons.

The target area of observation is required to be so large that the optics of MASS must have a very wide-FOV imaging. Consequently, the image plane is necessarily very large (> 1 m^2) and curved. A very large number of pixels (~ 1 million) and a large image plane size characterize an unusual combination of difficult demands for MASS detector.

A large image-plane (> 1 m^2) could be directly interfaced with multi-anode PMT's (or other large-area photo-sensitive detectors) which with appropriate electronics perform photon counting for each pixel. This method would achieve the highest time resolution. Alternatively, the image plane could be covered with micro-channel plates (MCP) whose amplified signals could be fed to MAMA or to small sensors by light guides and image-size-reducing optics. (The use of light guides substantially reduces the level of signal photons and demands prior amplification of photons by micro-channel plate intensifiers.) Candidate detectors include MAMA's, CCD's, silicon detectors, or avalanche photo-diodes. In this paper we use a CCD for a purpose of illustrating the concept of the detection scheme, while detailed consideration will be reported elsewhere using PMT's and other devices as well.

A CCD sensor (8 x 8 super-pixel 512 x 512 array or a single large device of 4,096 x 4,096 pixels) will allow the finest segmentation of the FOV. The minimum requirement for observing the shower is one unit of typical CCD (512 - 1,024). Required detector weight for a CCD configuration would be the lightest of all the detector candidates for a MASS satellite with Fresnel-lenses and MCP's.

Showers can laterally develop in width to the order of 100m ~ 1 km, depending on the shower age and the atmospheric depth of a track after the shower maximum. For a detector with ~ 4,000 x 4,000 pixels which views ~ (1000 km)^2, the finest pixel size would correspond to about (250 m)^2. The shower has width of one or two pixels for low energy events. Highest energy or inversely developing showers at upper atmosphere would leave a streak of light in the CCD image with a width of several pixels after the shower maximum. However, the number of pixels can be reduced to 512 x 512 for observing air showers induced by protons, nuclei and gamma rays with incident angles less than 70 degrees, as they would not give any meaningful lateral information with > 250 m lateral segmentation.

The dynamic range of CCD can be significantly enhanced if we use two parallel units (fed with signals from the same MCP's by a final-stage signal-dividing prism): Two different sensitivities of CCD's (a 1 ~ 10^3 unit and a 10^3 ~ 10^6 unit with a filter) would expand the dynamic range of the detector system to 1 ~ 10^6 range. Passive cooling in space would benefit CCD units. Contemporary CCD's operate in a cryogenic mode with a noise of only several photo-electrons per sampling interval, allowing the Optical Density range of a single unit to be phototube equivalent, D ~ 5.0 (1 ~ 10^5 photo-electrons).

CCD's are not optimum with regard to temporal resolution. The best duty cycle currently available with the conventional, sequential column-row charge-transport scheme is ~ 1 msec. (Only very small CCD's can work at ~ 30 μs). The time-of-flight of the disc of air shower particles for a 10 - 100 km track is 30 - 300 μs, and the light streak can only be recorded in a single frame of current CCD's (~ 1 ms). Although there would be no temporal details for the shower data with current CCD's, the firm characteristic of a single frame "snapshot" is advantageous in reducing the dataprocess and data-relay requirement. Several high frame-per-second (fps) schemes have been developed: use of a fast clock of 100 MHz (from sub- to few MHz) already improves readout speed by a factor of 10 ~ 100. Much faster charge transport down to a few μs integration time has been considered by using parallel, simultaneous line-delivery of column charges. When a new parallel readout device becomes available in future, a CCD will be able to provide fast timing (~ few μs) for integration time and readout.

The event selection and trigger could be implemented by a "signal-inversion" comparator circuit (for CCD's) and/or low- and high-pass filters (for PMT's). The comparator adds the new single-frame charge signals to that of the inverted, preceding frame background data. The background upgrader provides the average of several preceding frame data which is continually updated. The comparator will continually compare the new frame with the past frames, and will trigger and record only when the non-zero difference of signals above the set threshold is recognized.

The background upgrader can automatically remove almost all the "stable" gray-level contamination ($t > 1$ ms) from stray lights at dawn and dusk periods, meteorite's streak of lights, ground artificial lights and stellar reflections by clouds. The maximum acceptable signal level will be set for a trigger condition so as to eliminate the pixels that are directly hit by cosmic rays or trapped radiation. An efficient reduce algorithm for "pre-trigger alert" and trigger-decision must be implemented to eliminate these "false" triggers. The distinctive space-time characteristics of the "signal" (10 - 300 μs over dozens of contiguous pixels in a line) can be used for this purpose by PMT's and/or parallel read-out CCD's, as the single-particle false signals are spatially random and last for only 0.1 - 10 nsec.

4. OPTICAL SYSTEM

Innovative optics are required to observe a wide Field-of-View of $(500 \sim 1{,}000\ \mathrm{km})^2$ from an orbit of ~ 1,000 km or less. A cone angle (radius) of ~ 30° is required. At the same time a 2 ~ 4 m diameter objective is required. Multiple Fresnel lenses and catadioptric optics have been examined to achieve the required FOV and resolution (< 0.06°) with a large aperture of 1 ~ 2 m radius (**Fig. 7**).[5] Each pixel views ~ 1/4000 of this angle (or 1/512 for super-pixel mode). The sub-tending angle of a resolution element is ~ 1 arc minute (or 7 arc minute). Unlike Hubble ST or AXAF, MASS is 10^4 times more tolerant than the diffraction limit, and much more economical, segmented and unphased lens/mirror is acceptable. An orbital inflatable mirror of 14 - 32m D remains as a future possibility for a catadioptric mirror option, although it is not suitable for a very wide FOV (< 40° ~ 50° diameter).

The air shower signals are concentrated in three major N_2 lines in 330 - 400 nm range, and a suitable UV band-pass filter would be used. Photo-cathodes of MCP are available which have quantum efficiency ~ 0.25 for this wavelength. The phosphor screen at the end of MCP delivers a photon gain of ~ $10^{3\sim4}$. A few steps of tapered and straight light-guides, a final-stage MCP, and demagnifying lenses will guide the large image of the focal plane to the size of CCD camera (~ 6 cm). (Multi-anode PMT detector array (1- 2 m D) do not require these light guide scheme.)

CCD does not normally require an opaque shutter, but CCD with MCP's and PMT system need to close out from over-exposure to such bright lights as direct or reflected sun light in the day phase.

On-board event selection and trigger must be designed in an automatic mode to use the preceding background data most effectively. They are directly fed to the new signals, adding the negative of the last average of background frames (or low-pass data), and the resulting non-zero signals, if above the set threshold, will be picked up for pre-trigger alert. The majority of the detector's troublesome noise would be direct hits by cosmic rays and trapped radiation, which can be controlled in several ways; such as ignoring the data while passing the trapped belt, cut-off of high pulse heights, and requiring gradual increase-decrease profile of pulse heights in contiguously hit pixels over several continuous integration time bins (> 1 μs).

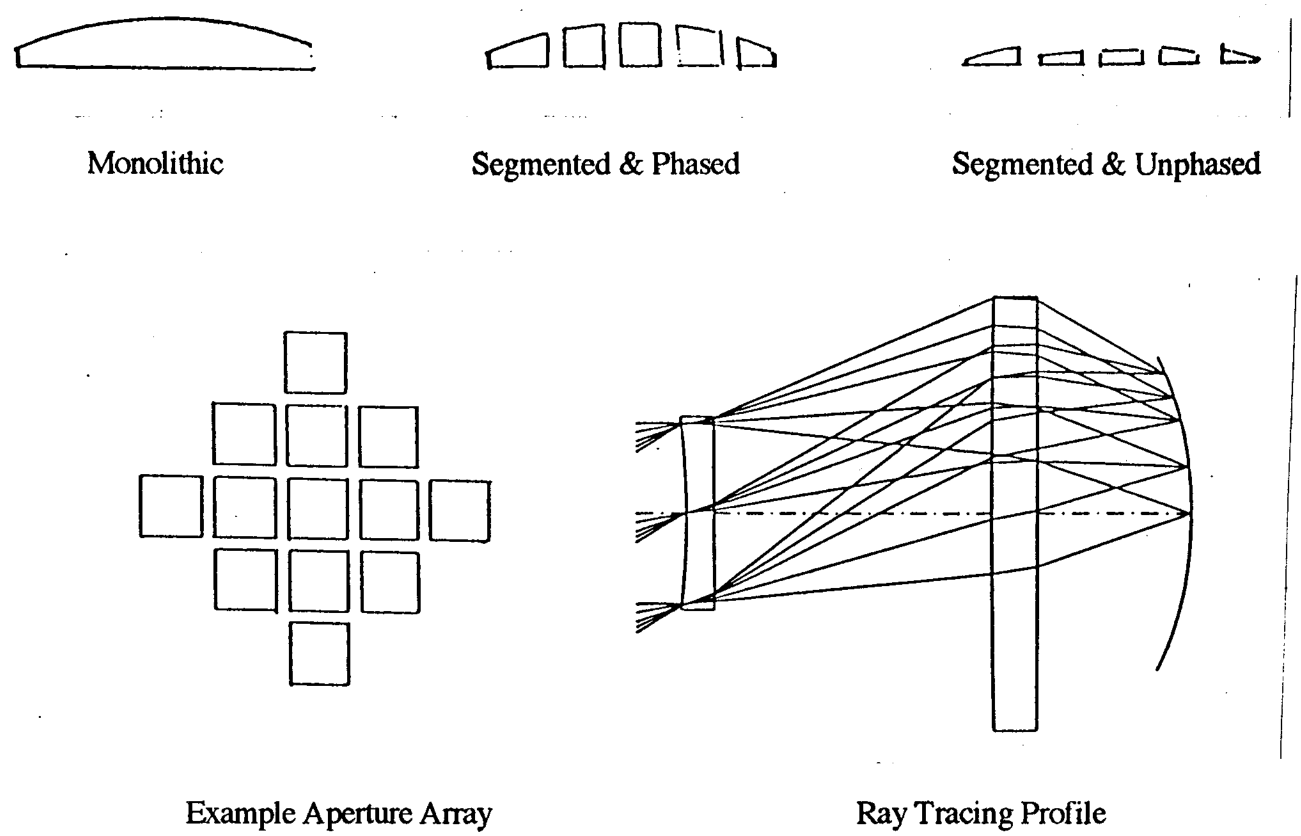

Fig. 7 A large aperture and wide FOV optics, using unphased, segmented, double Fresnel lenses. (Chipman, 1995;[7] Chipman et al., 1996[18]).

Other spurious events are lightning that have a rise time of ~ 100 μsec and last for ~ 1 msec (several msec for damping). Lightening will show high signals for several CCD frames, markedly different from a single-frame (30 ~ 300 μsec) and a single, straight-line image characteristic of an Auger Shower track. The recently discovered mysterious large-scale [~ 100 km)^3] upper atmospheric lightening, Elves and Sprites, and their UV characteristics are not known yet, but its light intensity is expected to be extremely bright for MASS detectors. Small meteorites and space debris will show a single streak which lasts for several seconds, shifting the position over many continual frames, following the motion of meteors relative to orbital velocity.

Gamma ray bursts (GRB)[19] produce Compton electrons when they enter earth's atmosphere, causing transient, global-scale fluorescence in the upper atmosphere. Sacco and Scarsi estimated that the GRB's of the size greater than 2 x 10^{-7} ergs / cm^2 sec could be detected by MASS.[20]

These subjects do have their own merit for observation. Logic to select them by separate trigger methods would be, however, more complicated than simply selecting an AS event. Multi-disciplinary applications of MASS to various atmospheric and astrophysical phenomena have been considered by Italian group for an international, inter-disciplinary observatory, "AIRWATCH".[21]

Selection of suitable satellites is limited for a MASS mission, requiring an accommodation of folded large optics that must be mechanically unfolded on orbit. An equatorial or very low inclination orbit would make the MASS most effective, when considering radiation background, aurora, night-duration, longest ocean coverage, least artificial light and other light.

5. EXPECTED NUMBER OF EVENTS

An estimate of the observable energy range depends on the geometric factors of the system and the night-sky observational time. For the sake of simplicity, we use 1/6 of the orbiting satellite time for the AS observation, and an area coverage of 10^6 km^2. Our view will have a zenith angle view of almost 2π for AS incidents ($> 2\pi$ for ν's), but we use only one π steradian for protons and nuclei because of the $\cos\theta$ dependence of area-solid angle (while it is still $> 2\pi$ for ν's). For a conservative estimate of the number of detectable events, we ignore very horizontal showers and all the possible neutrino and gamma ray events which might substantially increase the statistics above 10^{20} eV. (Neutrino and gamma ray events from topological defects could be of the order of > 1 ~ 10 events per day above 10^{20} eV.)

The threshold energy depends on the absolute signal strength (S ~ 1/distance^2), the size of a mirror ($S \propto R^2$), and the background level ($B \propto$ pixel size^2 / fps). We use here R = 1 m and pixel size 1 km for simplicity. In image differential method, $S/\sqrt{(<B>)} > 5$ will decide the threshold value. The average background intensity (<B>) is well known. The existing night-sky satellite data at 600 km give the continuum night-sky background in 330 - 400 nm range as 3 ~ 7 x 10^4 photons / m^2 μsec sr.[22] It is low enough that signals of showers with energy above 10^{20} eV (or 4 x 10^{20} eV) can be triggered from 500 km orbits (or 1000 km orbit) with 1 msec integration time for the ordinary CCD.

For integration times of a few μsec, ~ 1.2 x 10^{19} eV will be the threshold for $S/\sqrt{B} > 5$ selection from 500 km orbit, and ~ 5 x 10^{19} eV from a 1,000 km orbit. These values may be affected by other factors than the UV backgrounds. The threshold energy might become higher if $S/\sqrt{B}$ must be set higher than 5 in order to more efficiently eliminate false triggers that could arise from single particle events. The increase of aperture from R = 1 m to R = 2 m increases the signal by a factor of 4, which would significantly compensate any of these factors.

For the satellite operation of 1 year, an integrated exposure of the order of ~ 5 x10^{11} m^2 yr sr would become available. This corresponds to ~ 1/2 trillion events at 10^{16} eV. If we assume, for the sake of exercise, that the primary cosmic ray spectrum simply continues to 10^{23} eV with the $E^{-3.0}$ spectrum, with the integral intensity at 10^{16} eV as 1/m^2 yr sr, we should observe 5,000 events above 10^{20} eV and 0.5 events above 10^{22} eV per year. If we use only the 2 well-qualified events so far observed by Fly's Eye[23] and AGASA[24] for an estimate of the intensity above 2 x 10^{20} eV, we expect a few times 1,000 events per year for hadronic cosmic rays above 10^{20} eV.

6. SUMMARY

A concept for observing maximum-energy Auger showers from a satellite is presented. The existence of a significant flux of hadrons at energies above 10^{20} eV would challenge the present understanding of their source and propagation. Innovative optics and recent promising, fast digital imaging and signal-processing advances provide sufficient motivation to study and plan such an experiment, although several engineering studies are still needed. With a satellite, air showers could be observed to the energy region around 10^{22} eV. The highest energy limit of such observation depends on the actual flux, the orbital height, FOV of optics, and a use of large angle shower events. Large angle showers are extremely important for the neutrino-induced component. Their cross section and shower rate is predicted to increase with increasing energy, and the Standard Theory (QCD and the Unified Theory) might be examined at the highest energies. Observation of neutrino and gamma ray events above 10^{20} eV would provide tests for the topological defect theory. More detailed and practical engineering studies and physics simulations are expected to proceed in the coming few years within the NASA program of the OWL Concept Study. Similar studies are planned in Europe with the Airwatch program.

7. ACKNOWLEDGMENTS

This work is supported at the University of Alabama in Huntsville by NASA, NAS8-38609 D.O. 161 and NCC8-65 Mod. 6 for the first feasibility study.

8. REFERENCES

1. J. Linsley, Phys. Rev. Lett. **10**, 146 (1963); Scientific American, **239**, 60 (1978).
2. K. Greisen, Phys. Rev. Lett., **21**, 1016 (1966);
G.T. Zatsepin and V.A. Kuzmin, JETP Lett. **4**, 78 (1966).
3. C. T. Hill, Nucl. Phys. **B224**, 469 (1983); C.T. Hill, D. Schramm and T.P. Walker, Phys. Rev. **D36**, 1007 (1987); P. Bhattacharjee and N.C. Rana, Phys. Lett., **B246**, 365 (1990); G. Sigli, S. Lee, D. Schramm and P. Bhatttacharjee, Science, **270**, 1977 (1995); G. Sigl., Space Sci. Rev. **75**, 375 (1996).
4. J. Cronin, Nucl. Phys. B, **28B**, 213 (1992); Fermilab Workshop (1995); APS (1995);
A. A. Watson, Proc. '94 Snowmass Summer Study, pp. 126 - 138, eds. E.W. Kolb and R.D. Peccei, World Scientific (1995); N. Hayashida et al., Phys. Rev. Letters, **77**, 1000 (1996);
A.A. Watson, Proc. 15th Euro. Cosmic Ray Symp., Perpignan, Nucl. Phys. B (in press, 1996).
5. J. Linsley, USA Astronomy Survey Committee documents (1979); Proc. Workshop on Very High Energy Cosmic Ray Interactions, Univ. of Pennsilvania, pp. 476 - 491 (1982); R.H. Benson and J. Linsley, Proc. Southwest Regional Conf. Astron. Astrophys., eds. P.S. Riherd and P.F. Gott,Texas Tech University, Texas, **7**, pp. 161 - 169 (1981); Proc. 19th Intern. Cosmic Ray Conf., La Jolla,**3**, 438 (1985); *MASS/AIRWATCH, Huntsville Workshop Report*, pp. 34 - 74 (1995).
6. Y. Takahashi, Proc. of 24th International Cosmic Ray Conference, Rome, **3**, 595 (1995); *MASS/AIRWATCH Huntsville Workshop Report*, pp. 1 - 16 , Univ. of Alabama in Huntsville (1995); Proc. IInd Rencontres du Vietnam, "Sun and Beyond", Oct., 1995, Ho-Chi Minh City, ed. Tranh Thanh Van, World Scientific, (in press, 1996).
7. R. A. Chipman, J. O. Dimmock, L. W. Hillman, D. J. Lamb and Y. Takahashi, University of Alabama in Huntsville, preprint, unpublished, (1996).
8. K. Greisen, 9th ICRC, London, **2** 609 (1965); A.N. Bunner, Ph.D thesis, Cornell (1967);
K. Suga, Proc. 5th Inter-American Seminar on Cosmic Rays, Bolivia (1962).
9. T. Hara and G. Tanahashi et al., Acta. Phys. Acad. Hungaricae, Supple. **3**, 29, 369 (1970).
10. R.M. Baltusaitis et al., Nulc. Instr. Meth. **A240**, 410 (1985);
11. H.J. Christian, private communication (1994); *MASS/AIRWATCH Hunstville Workshop Report*, pp. 160 -210, University of Alabama in Huntsville (1995); J. Geophys. Res. **94**, 13,329 (1989).
12. R. Barry Johnson, Optical Engineering, **27**, 1046 (1988).
13. F. Halzen et al., preprint, University of Wisconsin, (1995); Quigg et al, Phys. Rev. Lett. 57 (1986).
14. H. Sato and T. Tachi, Prog. Theor. Phys.**47**, 1788 (1972); and in this proceedings (1996).
15. P. Bhattacharjee, in Auger Project Workshop Report (1995).
16. T. Hara and H. Sato, Prog. Theor. Phys. **65**, 477 (1981).
17. F. W. Stecker, ApJ 228, (1979).
18. R. A. Chipman, *MASS/AIRWATCH Huntsville Workshop Report*, pp. 276-282 (1995).
19. G. J. Fishman and C.A. Meegan, ARA&A, **33**, 415 (1995); G.J. Fishman, *MASS/AIRWATCH Huntsville Workshop Report*, pp. 211-256 (1995).
20. B. Sacco and L. Scarsi, Rome Workshop *MASS/AIRWATCH*, August 4, unpublished (1995).
21. L. Scarsi and J. Linsley, private communication/unpublished (1996).
22. R. R. Meier, Space Science Rev. **58**, 1 (1991).
23. D.J. Bird et al., ApJ **424**, 491 (1994); E.C. Loh, *MASS/AIRWATCH Huntsville Workshop Report*, pp. 75-159 (1995).
24. N. Hayashida et al., Phys. Rev. Lett., **73**, 3491 (1995).

NASA
National Aeronautical and Space Agency

Report Document Page

1. Report No.	2. Government Accession No.	3. Recipients Catalog No.

4. Title and Subtitle

FNAS/Cosmic Ray-Air Shower Measurement from Space
Cosmic Ray Research

5. Report Due

11/17/1996 Final

6. Performing Organization Code

7. Author(s)

Y. Takahashi

8. Performing Organization Report No.

10. Work Unit. No.

9. Performing Organization Name and Address

The University of Alabama in Huntsville
Huntsville, Alabama 35899

11. Contract or Grant No.

NAS8-38609 D.O. 161

13. Type of report and Period covered

FINAL

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, DC 20546-001
Marshall Space Flight Center, AL 35812

14. Sponsoring Agency Code

NASA

15. Supplementary Notes

16. Abstract

A feasibility study was performed to observe from space the highest energy cosmic rays above 10^{20} eV. A satellite observatory concept, the Maximum-energy Auger (Air)-Shower Satellite (MASS), is recently renamed as the Orbital Wide-angle Collector (OWL) by taking its unique feature of using a very wide field-of-view (FOV) optics. A huge array of imaging devices (about 10^6 pixels) is required to detect and record fluorescent light profiles of cosmic ray cascades in the atmosphere. The FOV of MASS could extend to as large as about 60° diameter, which views (500 - 1000 km)^2 of earth's surface and more than 300 - 1000 cosmic ray events per year could be observed above 10^{20} eV. From far above the atmosphere, the MASS/OWL satellite should be capable of observing events at all angles including near horizontal tracks, and would have considerable aperture for high energy photon and neutrino observation. With a large aperture and the spatial and temporal resolution, MASS could determine the energy spectrum, the mass composition, and arrival anisotropy of cosmic rays from 10^{20} eV to 10^{22} eV; a region hitherto not explored by ground-based detectors such as the Fly's Eye and air-shower arrays. MASS/OWL's ability to identify cosmic neutrinos and gamma rays may help providing evidence for the theory which attributes the above cut-off cosmic ray flux to the decay of topological defects.

17. Key Words (Suggested by Author (s))

Cosmic Rays
High Energy Radiation
Space Optics
Astrophysics

18. Distribution Statement

cc: LA20	(1)
EM11/D. Hipp	(1)
ONRRR	(1)
ES75/M. Robinson	(2)
NASA/CASI	(2)
Schroer/UAH	(1)

19. Security Class. (of this report)	20. Security Class. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified		