Physics, Instrumentation and Fluorescence Energy Measurement

Auger Collaboration Meeting

Malargue, Argentina

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University of New Mexico

November 14, 2000

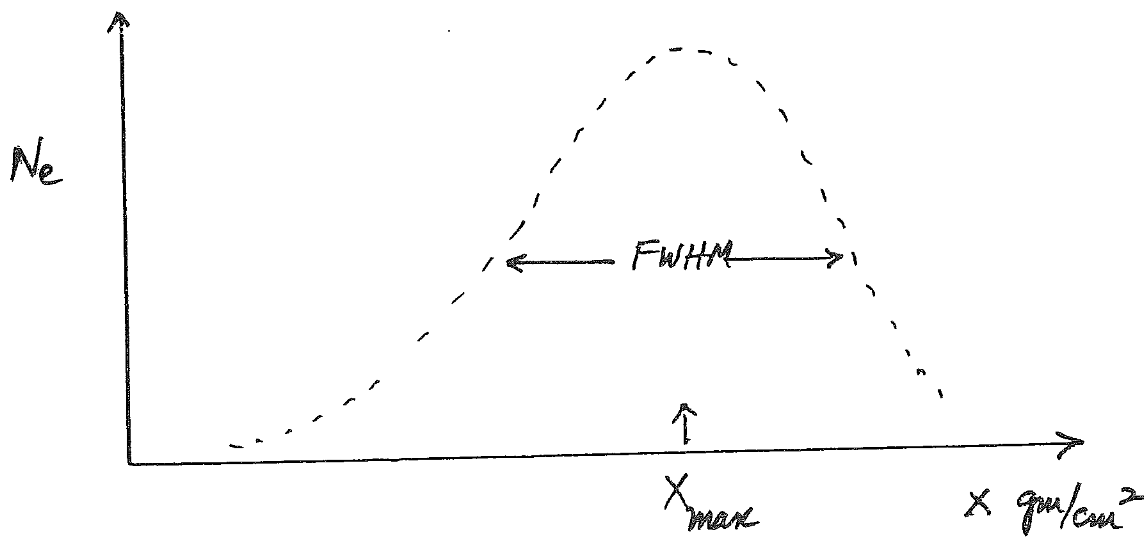
- What does a 10^{20}eV shower *look like*?

- What happens *in practice*?

- What are the sources of error in the energy measurement?

- The details ... a few (selected) examples

What does a 10^{20} eV shower "look like"?



a) In "grams":

$X_{max} \sim 820$ gm/cm^2

FWHM $\sim 2.35\sigma \approx 494$ gm/cm^2 $\quad$ ($\sigma \sim 210$ gm/cm^2)

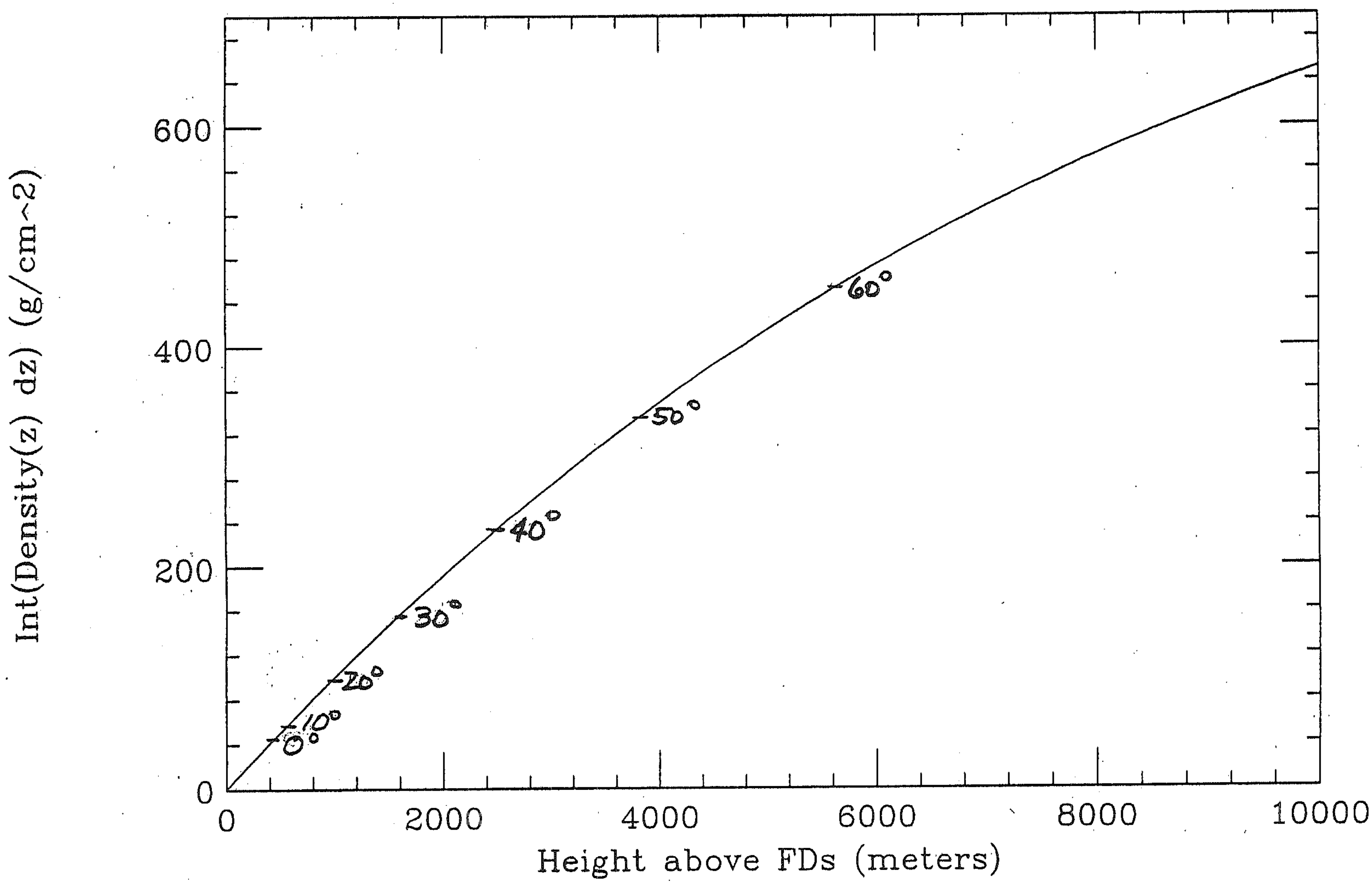
b) In "the atmosphere":

For a "average" Auger shower at zenith angle ~ 30°, then X_{MAX} is 1.5~2 km above ground level (≡ 1500 m),

and

FWHM is 5.5~6 km ≡ 18~20 μsec

Int(rho(z) dz) above Auger Fluorescence Detectors



US Standard Atmosphere

Auger (nominal) elevation = 1500m

$\mathcal{f}$ X_{max} = 820 gm/cm^2 (typical at 10^{20} eV)

... and the fluorescence signal?

To 0^{th} order the shower energy is dissipated in the atmosphere over the FWHM distance:

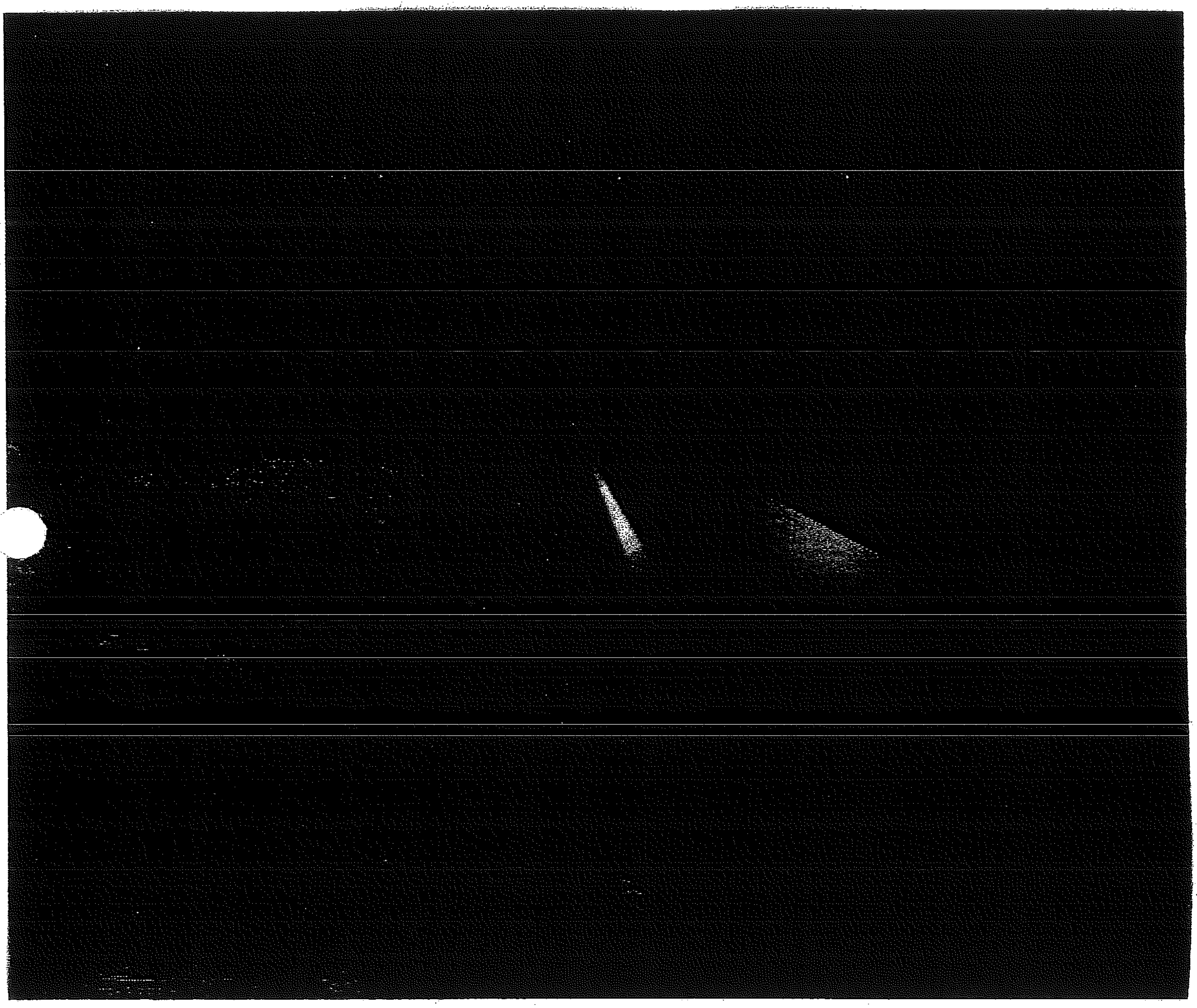
$$\text{Power} = \frac{\Delta \text{Energy}}{\Delta \text{time}}$$

$$\simeq \frac{10^{20}\,eV \times 1.6 \times 10^{-19}\,J/eV}{\sim 18 \times 10^{-6}\,s} \equiv \frac{16\,J}{18\,\mu sec}$$

$$\simeq \frac{8}{9}\,\text{Mwatt}$$

the typical fluorescence efficiency is .005% (ie 50 ppM of the energy is reemitted in N_2 fluorescence light between 300 ~ 400 nm):

So a $10^{20}\,eV$ shower is a $\left(\frac{8}{9}\right)$ 50 watt, relativistic, UV, light bulb.



What happens "in practice"?

a) the fluorescence detector "cameras" take a "video" of the air shower!

✓ In other words the fluorescence detectors are "simply" high speed cameras.

✓ They view "the shower development" and provide (potentially) a direct path to the measurement of the shower energy

✓ The fluorescence information, combined with ground array information for hybrid events, provide essential cross checks for our study of the highest energy cosmic rays.

... but for quantitative information (from the fluorescence detectors) we need to get all the "important details" correct!

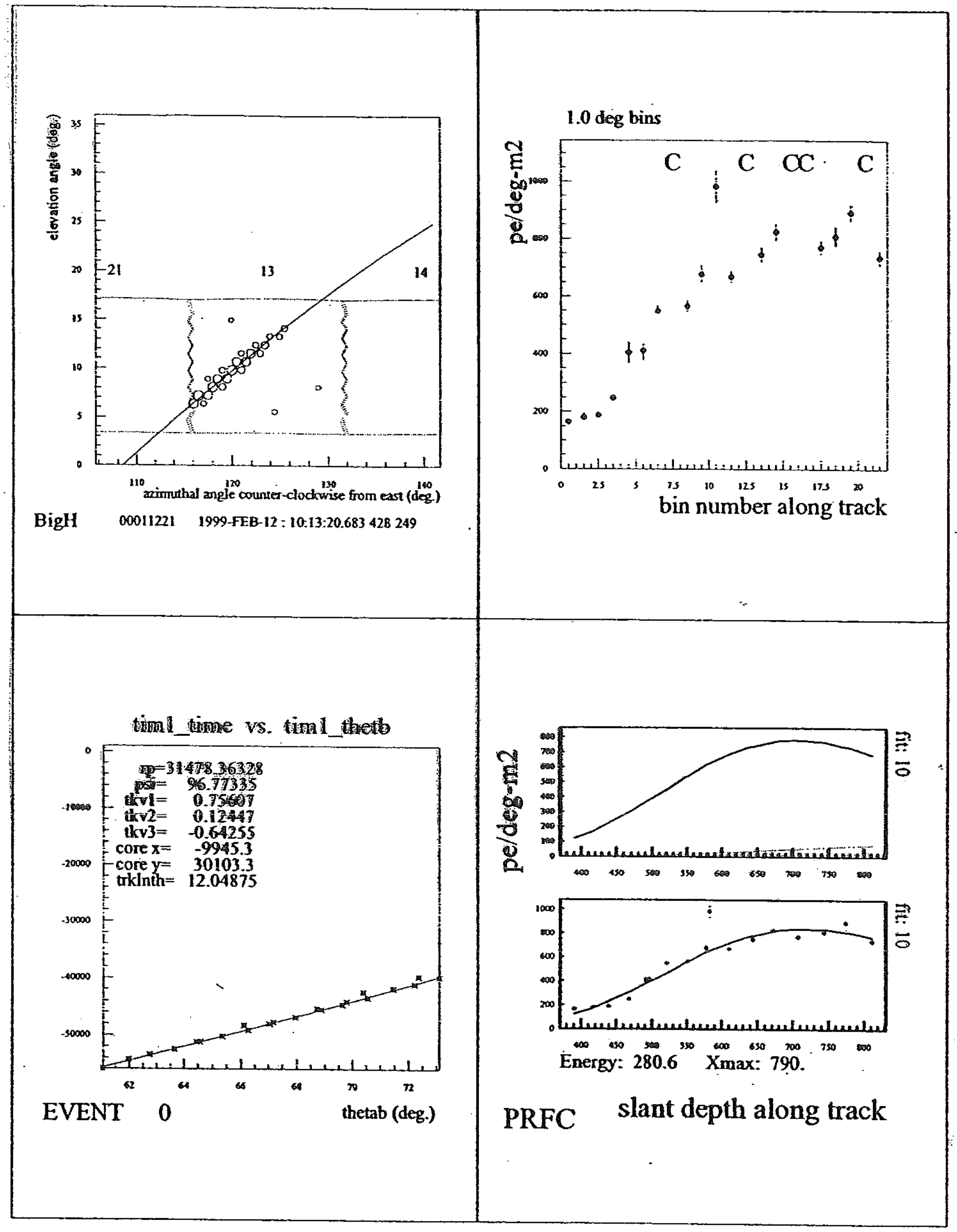


Figure 9.10. BigH event recorded on 02/12/1999. Highest energy event seen by BigH.

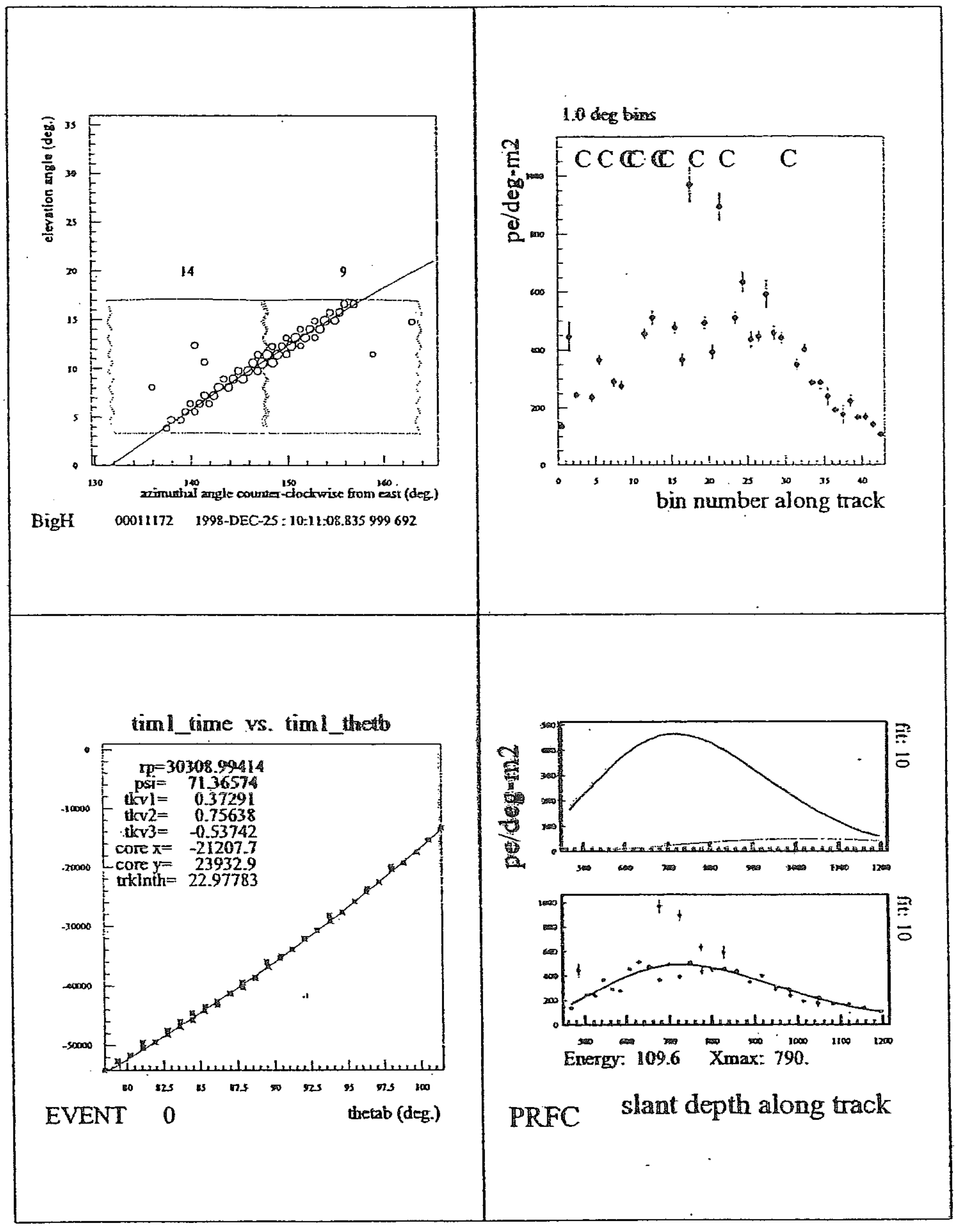


Figure 9.9. BigH event recorded on 12/25/1998.

b) What are the "important details"?

i) (light) source:
- ✓ fluoresence spectrum (λ) and efficiency
- ✓ air cherenkov (background)
- ✓ collisional energy / missing energy
  "dE/dx" "ν's, μ's,"
- ✓ night sky etc. (backgrounds)

ii) (light) transport:
- ✓ finite transmission
  - Rayleigh (molecular)
  - Mie (aerosols)
  - Ozone
- ✓ multiple scattered light
- ✓ clouds

iii) (camera) digitization:
- ✓ UV filter and other window components' transmission
- ✓ mirror reflectivity
- ✓ Mercedes [cracks in HiRes] efficiency
- ✓ PMT efficiency & calibration (PE ⟷ ADC)
- ✓ absolute calibration (γ ⟷ ADC value)
- ✓ electronics linearity (for range of signal sizes and signal durations)

iv) analysis:
- ✓ distance uncertainty to shower
- ✓ "energy integral"
- ✓ Monte Carlo (missing pieces relevant to fluorescence measurement)
- ✓ light counted <u>in</u> (versus <u>out</u>) of a track/shower

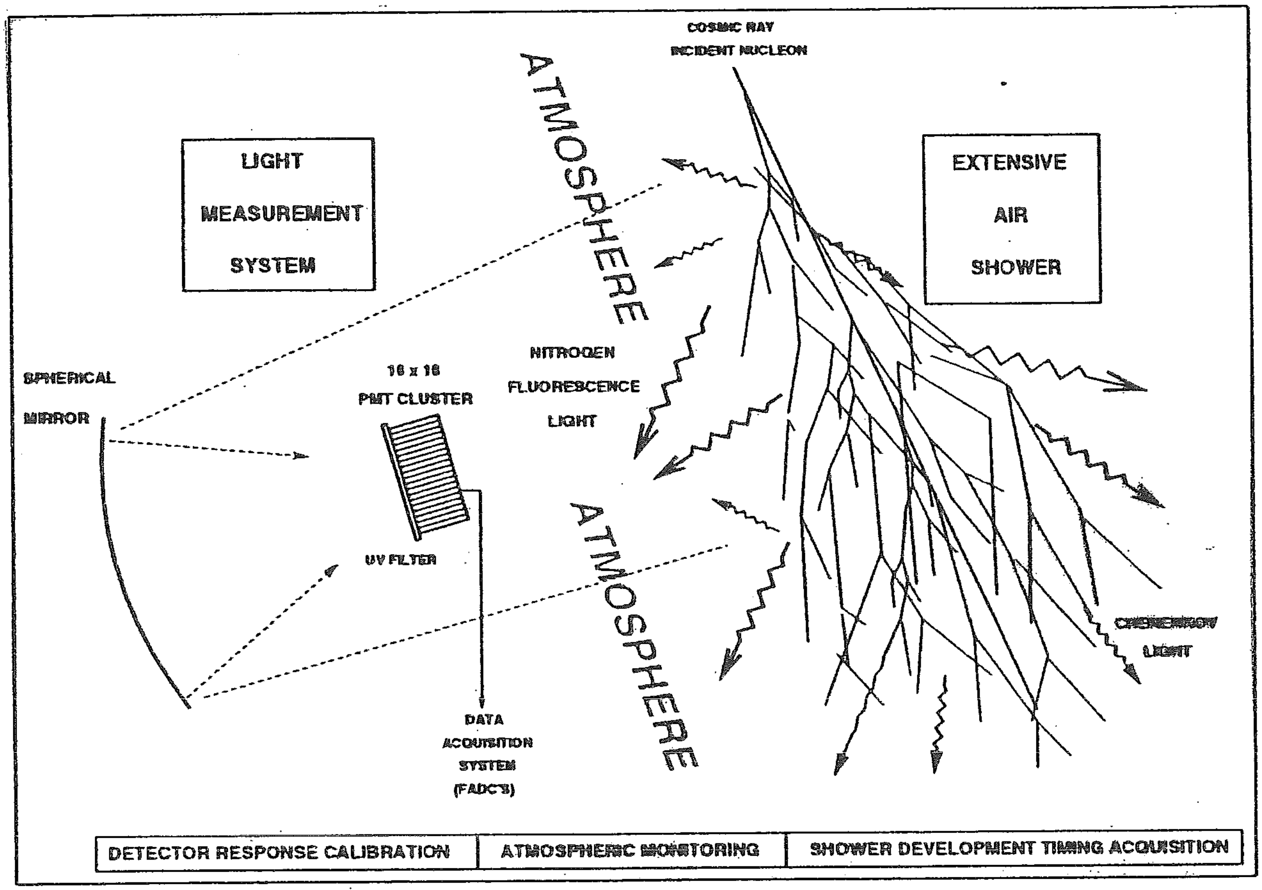


Figure 1.1. Air Fluorescence Technique.

Julien Girard, May 2000

c) there may be quite a few "important details"!

✓ thus beware of a "10% mentality" ... by which I mean the mind set that any given contribution to the energy uncertainty is adequately known/monitored when its contribution to $\frac{\Delta E}{E} \lesssim 10\%$.

(†)

✓ while contributions that tend to increase the reconstructed shower energy are particularly important (for a GZK experiment), contributions that tend to decrease the reconstructed energy must also be understood!

(††)

(†) ... else $\frac{\Delta E}{E} \sim \sqrt{n}\ 10\%$ and n may be large!

(††) ... else adding the uncertainties in quadrature may no longer apply,
and
we need to avoid creating a net shift in the reconstructed shower energies!

Magnitude of fluorescence energy measurement uncertainties:

a) Telescope Array proposal "estimates"

b) HiRes (unofficial) "estimates"

... while Auger fluorescence errors may be less than these in some cases:

- ✓ distance to shower (in hybrid events)
- ✓ end-to-end calibration (aided by Schmidt aperture, climate controlled enclosures, ...)
- ✓ Transmission corrections (showers are nearer)

both TA and HiRes transparencies excluded (~~potentially~~ several error sources:

- ✓ air Cherenkov subtraction
- ✓ multiple scattering corrections
- ✓ energy integral (extension over the full shower)

Table 4.2: Estimated systematic uncertainties of energy measurement

T.A. proposal (2000)

Item		Error	Comments
Number of photoelectrons	N^{pe}	5%	
Fluorescence yield	ϵ_{fl}	10%	inc. pressure uncert.
Distance to shower	R	5%	error in R^2
Detection efficiency	ϵ_{det}	10%	5% for mirror, 5% for filter, 8% for PMT, 3% for obscuration.
Energy loss rate	ϵ_{dep}	5%	
Atmospheric correction	T_M, T_{ray}	10%	
Missing energy correction	$E_{primary}/E$	5%	the primary particle mass dependences
TOTAL		20%	quadratic sum of all

Sources of error in Energy Measurement

Error	Size
Fluorescence Yield	10%
Atmosphere(Aerosols)	5-25% (*)
Optics (sampling fraction)	10%
Calibration(absolute)	10%
Geometry (stereo)	5%
Calibration(relative)	5%
Photo-statistics	5% ?
Mirror reflectivity	5%
Missing Energy	2%
UV filter	2%
Atmosphere(molecular)	2%

Auger "end to end" calib.

- Total Systematic Uncertainty in Energy ~ **21%**
  ↑ w/o atmosphere (*) term.
- Can provide a more solid lower limit on energy…Examples:
  - Assume that sigma in charge distribution is totally due to photo-electron statistics...
  - Assume no attenuation in atmosphere..

Lawrence Wiencke ... order of magnitude "estimates"

Is this "serious"?

✓ YES! And this is "even more true" while the issue of "super GZK" events is undecided!

AGASA: 7 ($\sec\theta \leq 1.4$) ~ 12 ($\sec\theta \leq 1.8$) events $> 10^{20}$ eV

$\downarrow$ (†)

2 events

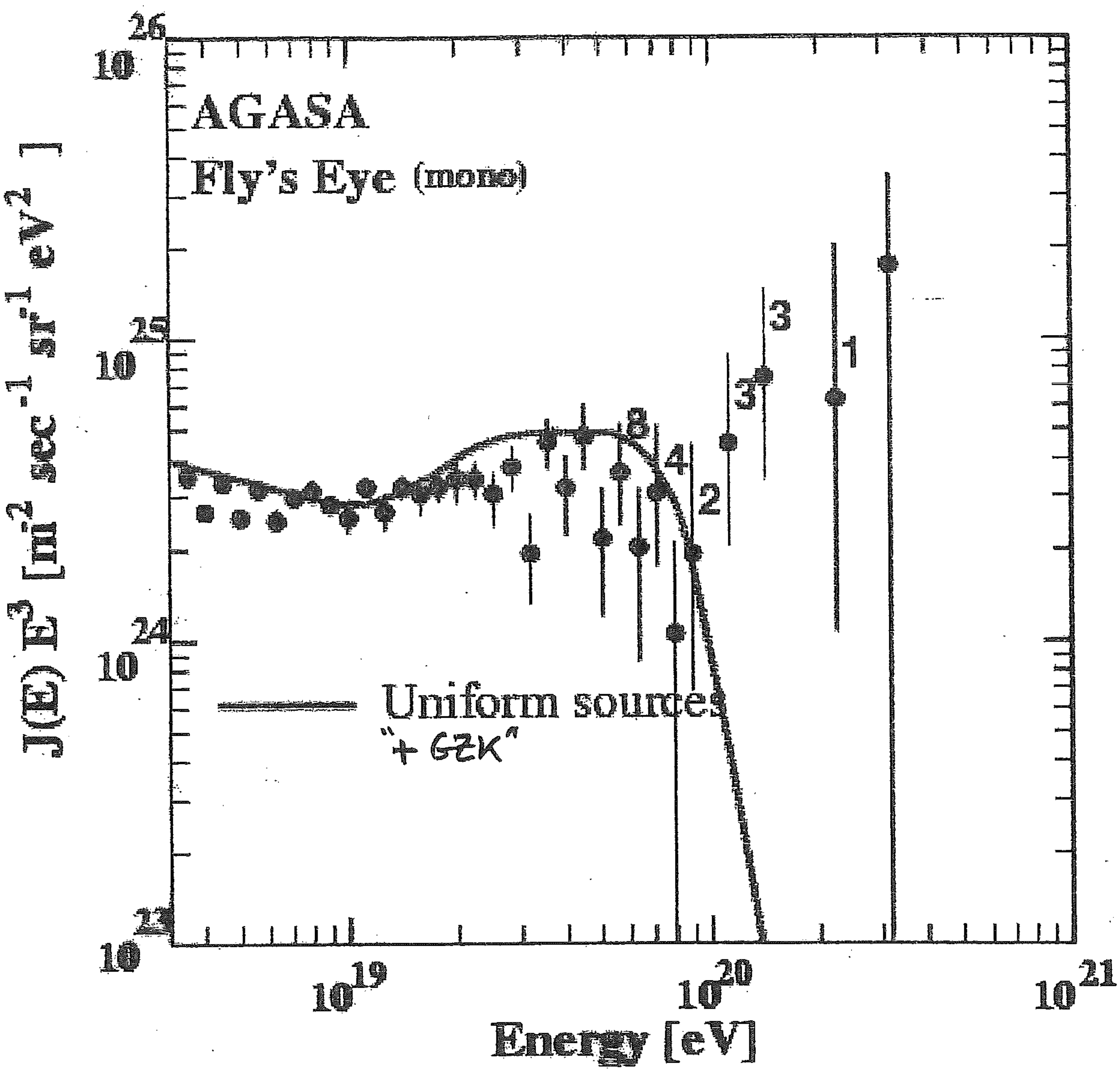
Hires : 7 events $> 10^{20}$ eV
(1999 ICRC)

$\downarrow$ (†)

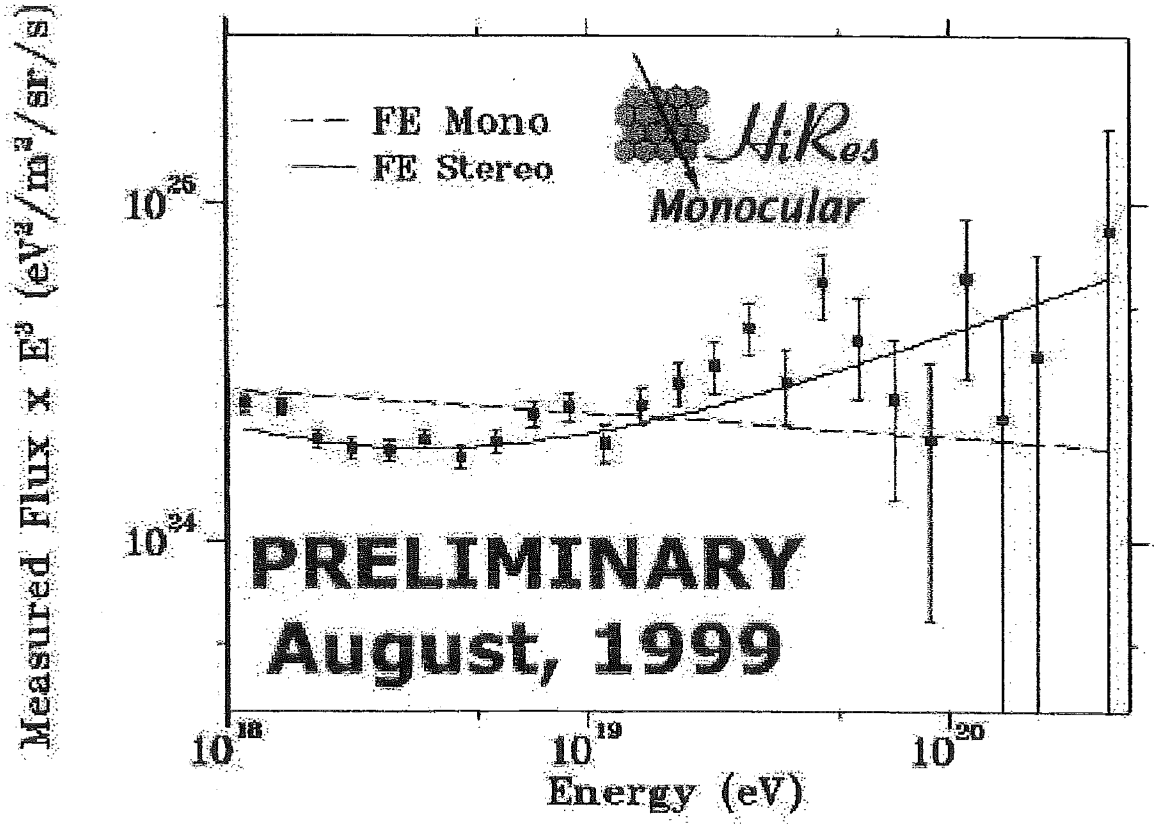
1 event

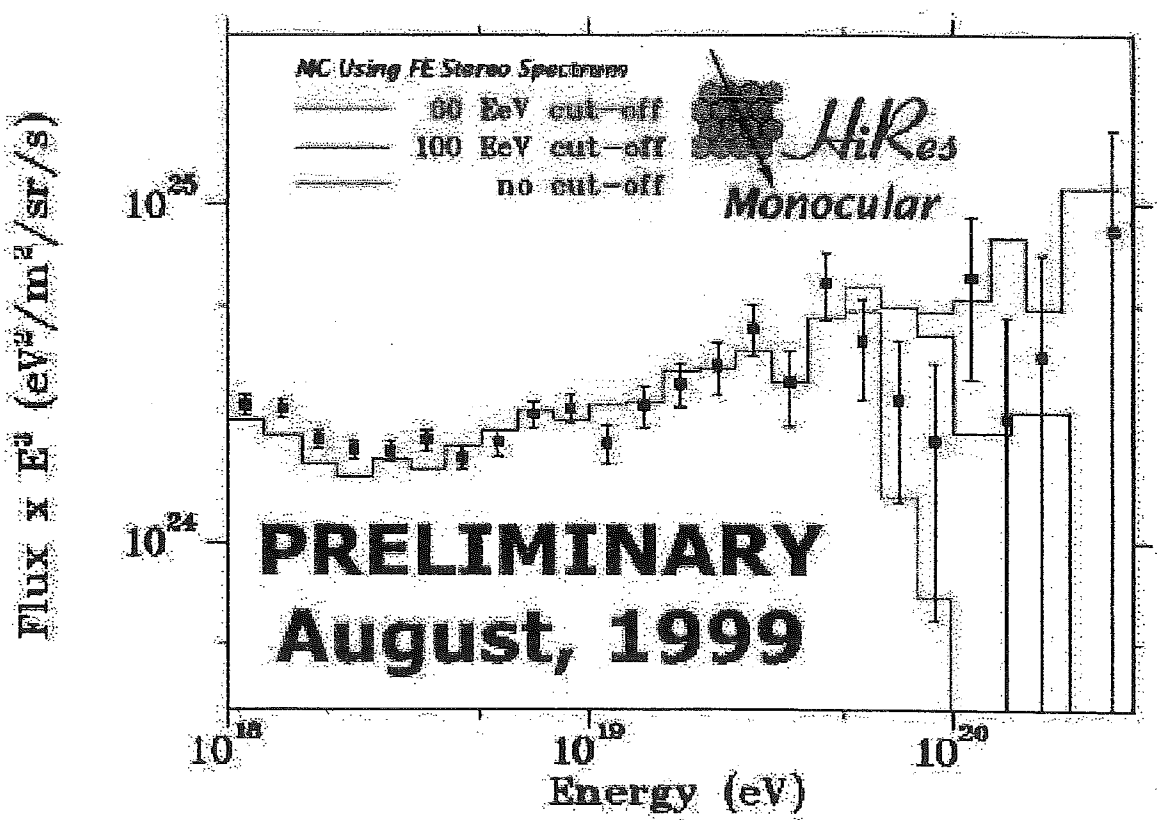
(†) when one (major) correction is made in the most conservative manner.

AGASA + Fly's Eye (monocular data)



HiRes Preliminary August, 1999





TZA

$> 10^{20}$ eV events

Table 9.10. Reconstructed energies for seven highest energy events assuming three different aerosol concentrations specified by the value of the aerosol horizontal extinction length. ↓ "nominal" ↓ "conservative"

event	E[EeV]: $L_M = 12$ km	E[EeV]: $L_M = 15$ km	E[EeV]: $L_M = \infty$
1	170.2	137.0	59.3
2	129.8	100.7	43.4
3	111.1	111.5	72.8
4	108.6	95.2	55.4
5	109.5	105.7	68.6
6	280.6	261.1	163.4
7	101.5	88.2	47.0

T. Abu Zayyad
Thesis, May 2000

A short overview of 4 uncertainties
... because the fun is in the details:

a) fluorescence yield (VS altitude)
"atomic physics"

b) transmission correction
"atmospherics"

c) energy integral
"analysis"

d) PMT calibration ("gain" measurement)
"instrumentation"

Air fluorescence yield (VS altitude)

- ✓ A fraction of (collisional ≡ dE/dx) shower energy in air is re-radiated in N_2 fluorescence light.
- ✓ The fraction depends on local T, P due to "quenching" in N_2–O_2 collisions
- ✓ The *effective* fluorescence efficiency depends on the detector wavelength acceptance.
- ✓ The strong wavelength (Rayleigh) dependence in atmospheric transmission biases distant showers to longer wavelengths.
- ✓ The most recent measurement of the fluorescence yield (Kakimoto et al [1996]) quotes 10% systematics:
  - i) Are Kakimoto et al and Bunner consistent?
  - ii) Can we do "even better" by combining Kakimoto and Bunner results?

2. Fluorescence Technique

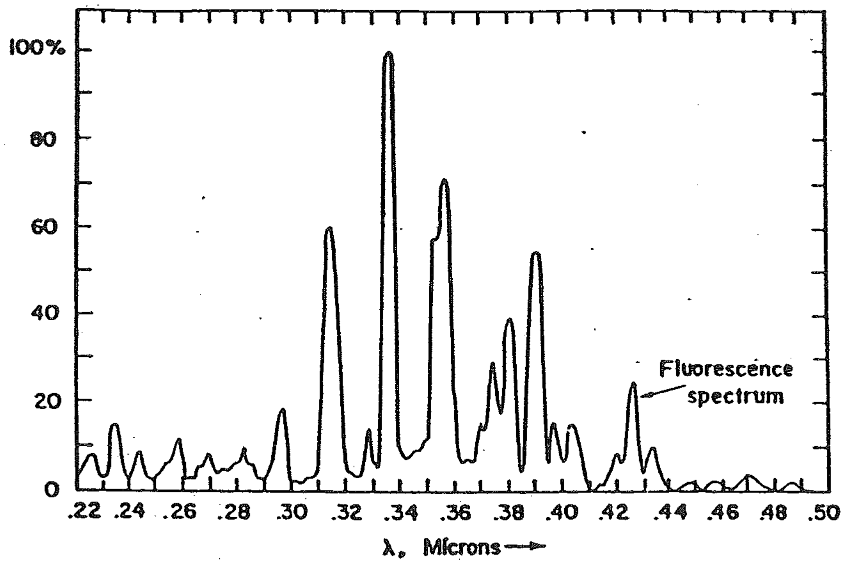


FIGURE 6.1 Spectrum of nitrogen fluorescence in the near ultraviolet.
(View 300~400 nm in Fly's Eye)

- ~.005% of collisional dE/dx in air appears in ***air fluorescence***:

  1. 50 keV electrons – G. Davidson and R.O'Neil, J. Chem. Phys. **41**, 3946 (1964)
  2. 4 MeV α's – A.N. Bunner, Ph.D. Thesis, Cornell U. (1964)(†)
  3. 1.4 to 1000 MeV electrons – F. Kakimoto, et al, N.I.M. **A372**, 527 (1996)

(†) Note: many fluorescence efficiencies called "Bunner" are an "average" of Bunner ⊕ Davidson & O'Neil ⊕ P. Hartman, LANL Report (1963).

Kakimoto et al

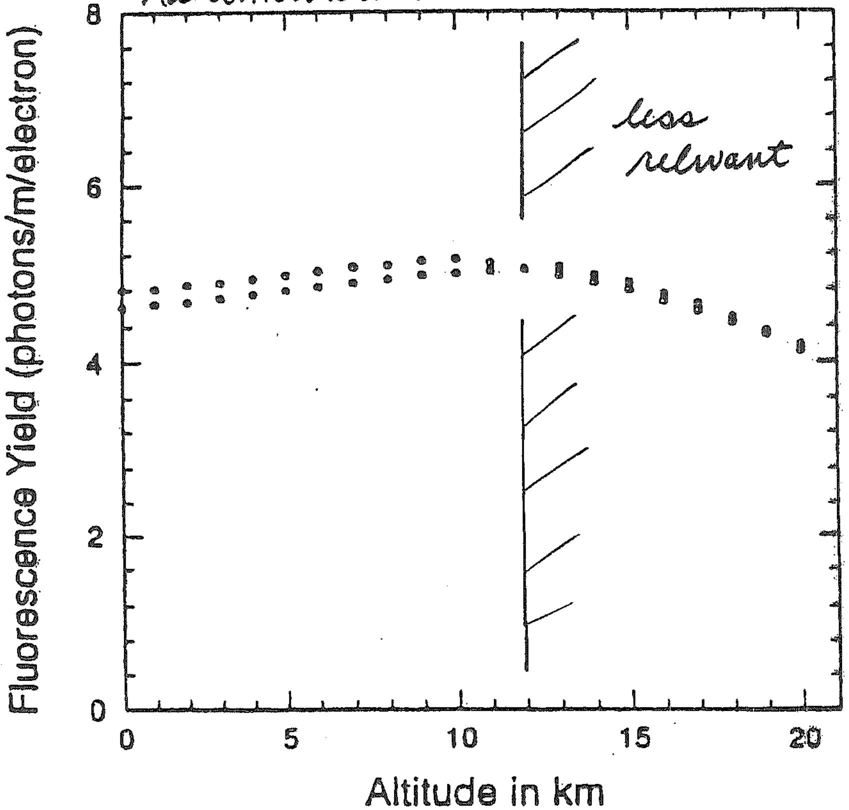


Fig. 9. Fluorescence yield between 300 and 400 nm of an 80 MeV electron as a function of altitude. This calculation employed a typical mid-latitude summer atmospheric model with a surface temperature of 296 K (closed circle) and a similar winter model with a surface temperature of 273 K (open circles).

"Bunner" ⊕ Fly's Eye acceptance : 310~440nm

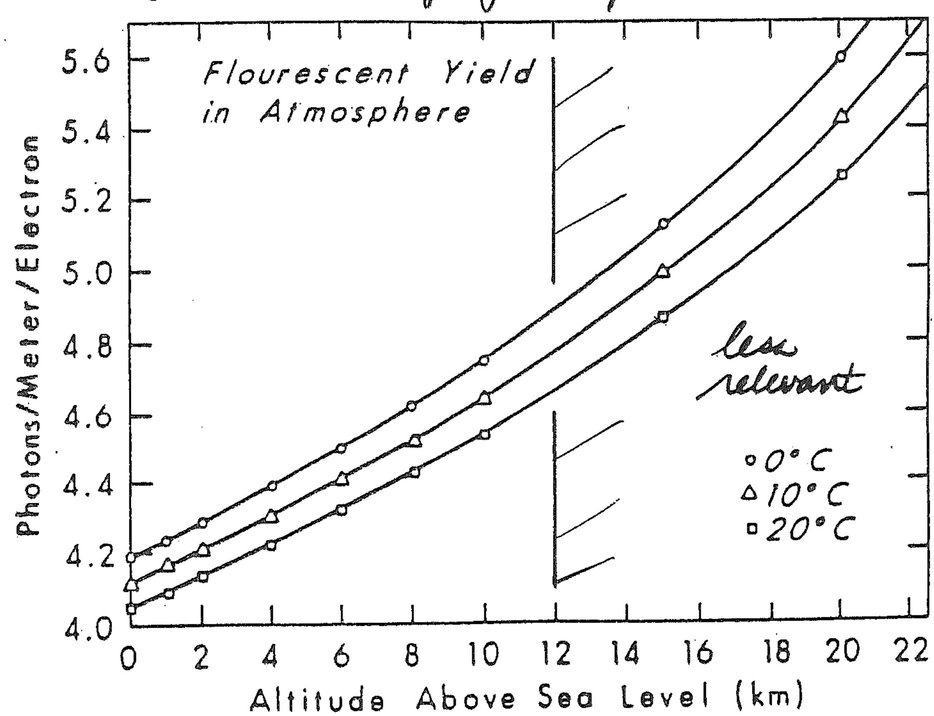


Figure 4.2: Altitude and temperature dependence of atmospheric fluorescence efficiency.

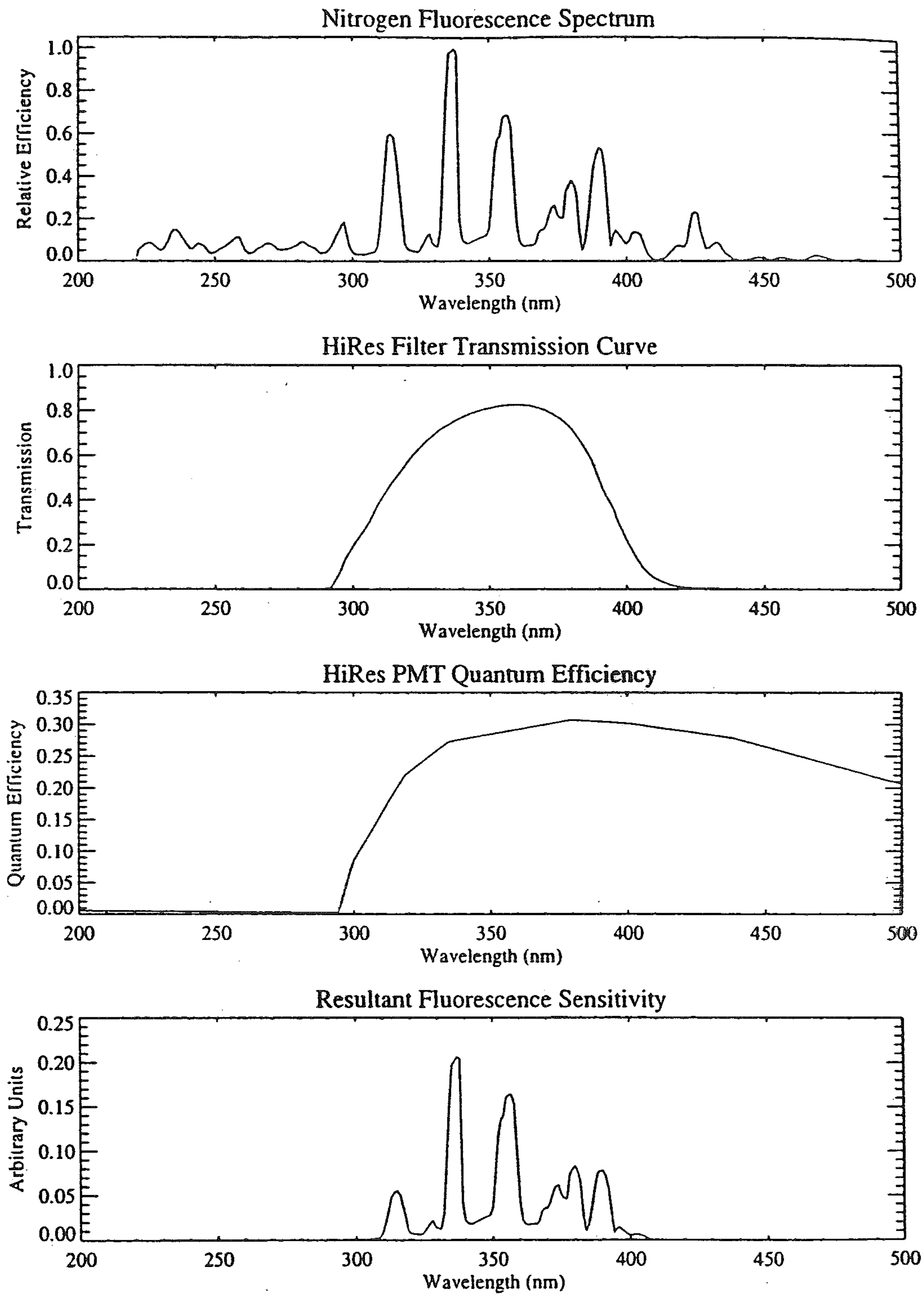


Figure 3.15: Resultant fluorescence spectrum after taking into account HiRes filter and PMT quantum efficiency.

C. Wilkinson, May 1998

2. Fluorescence Uncertainties

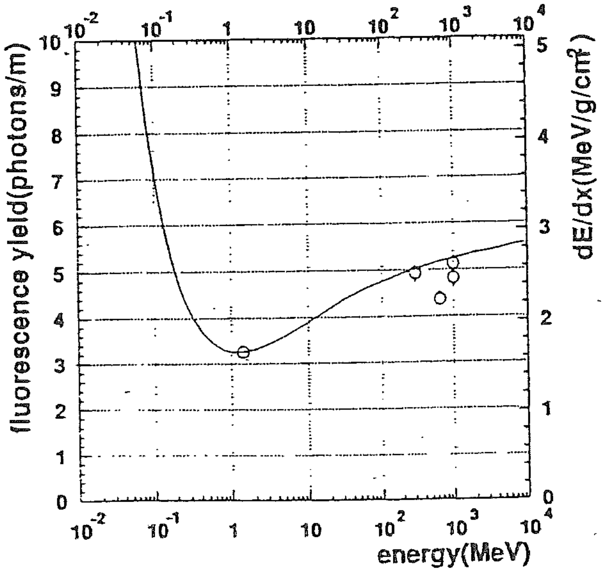
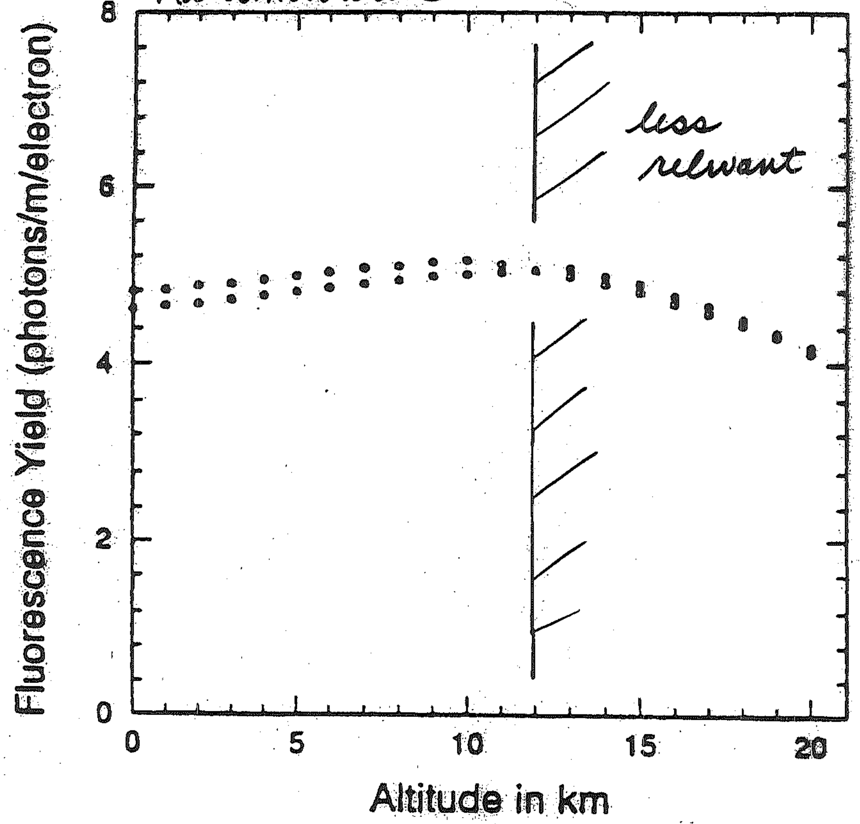


Fig. 7. Energy dependence of nitrogen fluorescence between 300 and 400 nm in dry air at a pressure of 760 mm Hg. The dE/dx curve is shown as a solid line. The scale of the fluorescence yield is adjusted so that the 1.4 MeV point lies on the dE/dx curve.

- *air fluorescence* yield:
  1. Fly's Eye quoted ±20% systematic uncertainty in fluorescence yield
  2. Latest laboratory calibration [F. Kakimoto, et al]:
     - includes a range of electron energies and air pressures
     - includes *Fly's Eye* broad band filter
     - ✱ statistical errors of 3% and systematic errors of 10%
  3. New fluorescence yield changes $E_{shower}^{Fly's Eye} < 2\%$
     - E.C. Loh and H.Y. Dai, Tokyo C.R.C. (1996)

Kakimoto etal



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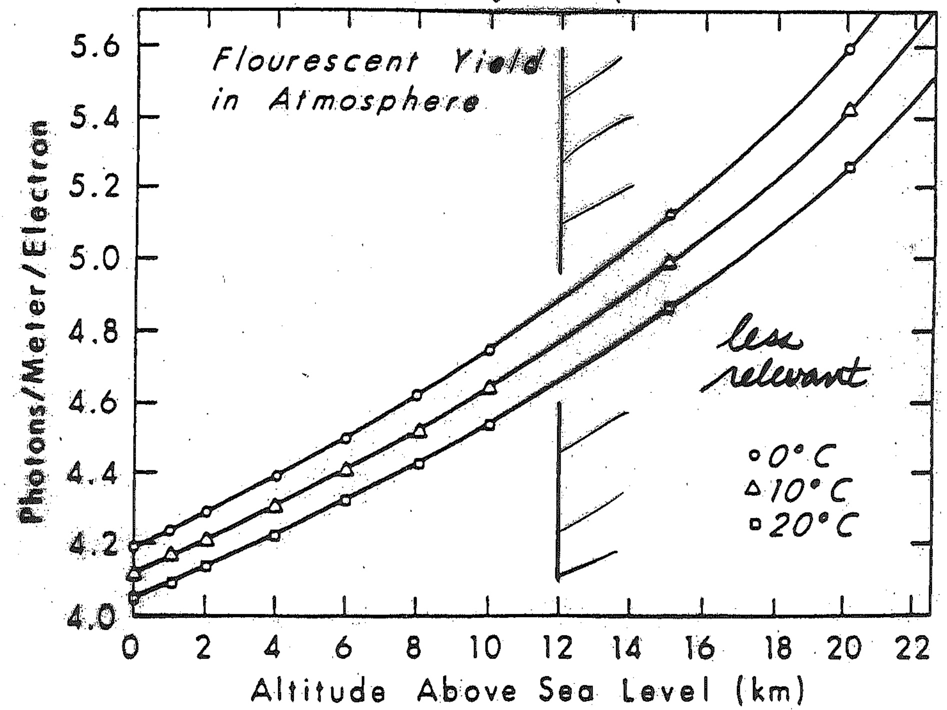


Figure 4.2: Altitude and temperature dependence of atmospheric fluorescence efficiency.

If consistent: Kakimoto = Bunner $\times \underbrace{\left(\frac{2.387}{2.180}\right)}_{\text{"}dE/dx\text{"}} \cdot \underbrace{(0.92)}_{\Delta\lambda \text{ acceptance}}$ = Bunner $\times$ 1.007

at 5km ~4.86 γ/m/e ⟷ ~4.35 × 1.007 = 4.38 γ/m/e

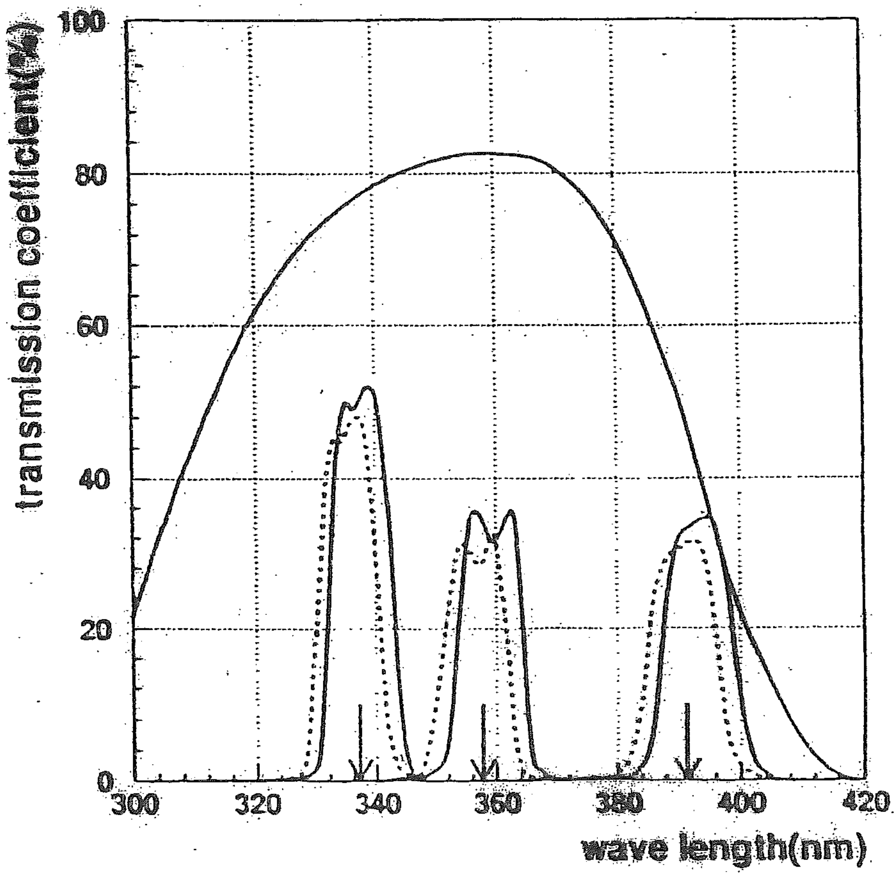
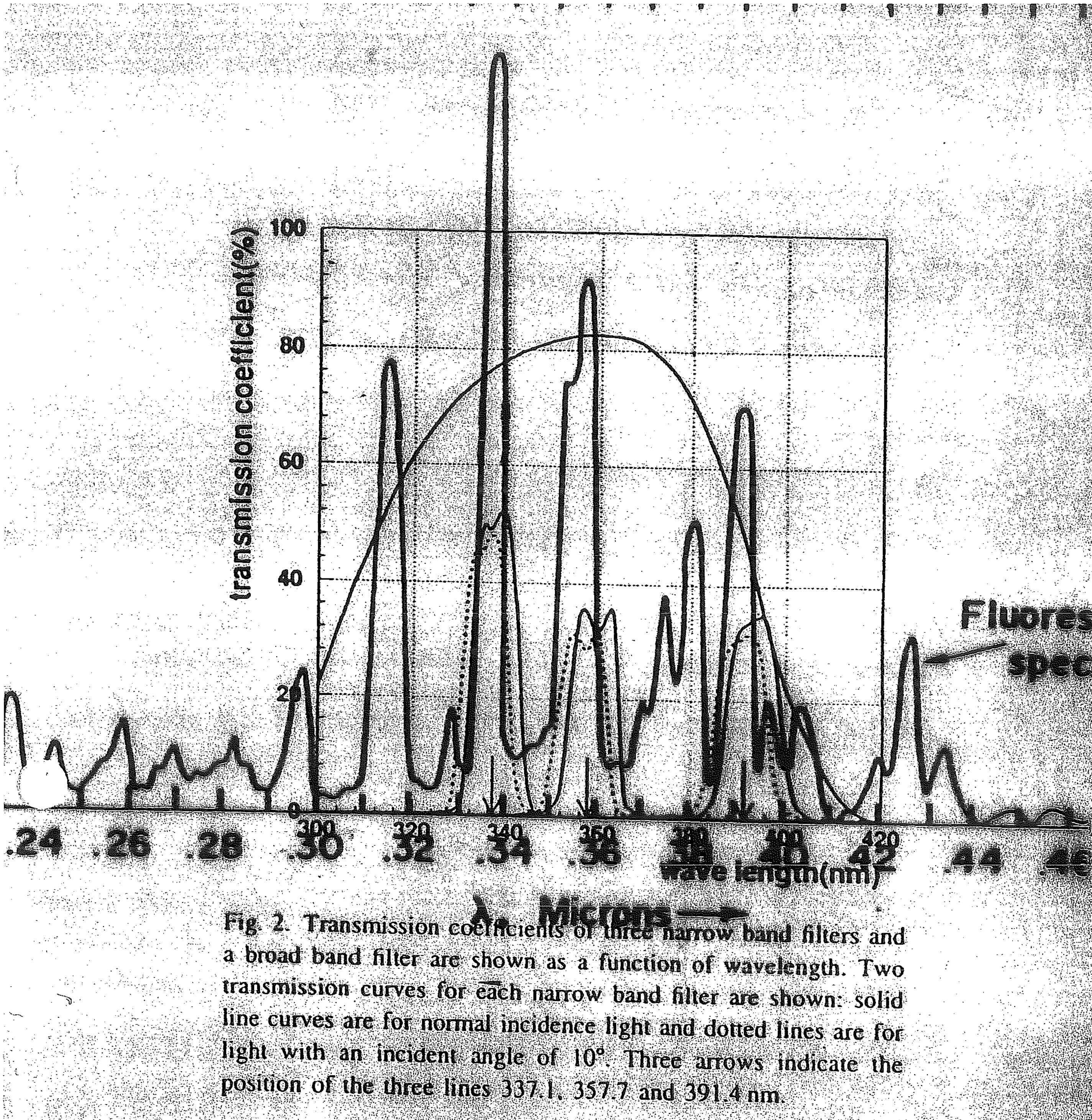


Fig. 2. Transmission coefficients of three narrow band filters and a broad band filter are shown as a function of wavelength. Two transmission curves for each narrow band filter are shown: solid line curves are for normal incidence light and dotted lines are for light with an incident angle of 10°. Three arrows indicate the position of the three lines 337.1, 357.7 and 391.4 nm.

Agreement between different measurements:

✓ closest agreement for 337.1 and 391.4nm lines

✓ poorest agreement for 357.7nm line
where Kakimoto yield ~ 22 ppm VS
Davidson & O'Neil ~ 15~18 ppm



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Agreement between different measurements:

ure 4.1: Atmospheric fluorescence spectrum in the near UV

✓ closest agreement for 337.1 and 391.4nm lines

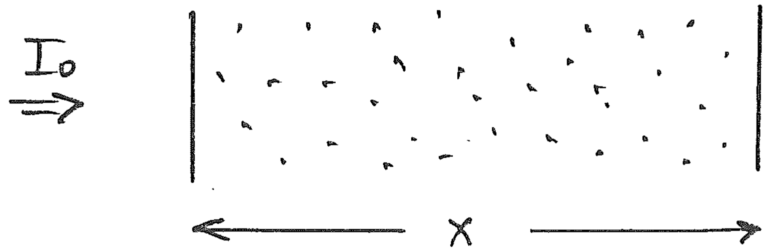
✓ poorest agreement for 357.7nm line

where Kakimoto yield ~ 22 ppm VS Davidson & O'Neil ~ 15~18 ppm

27

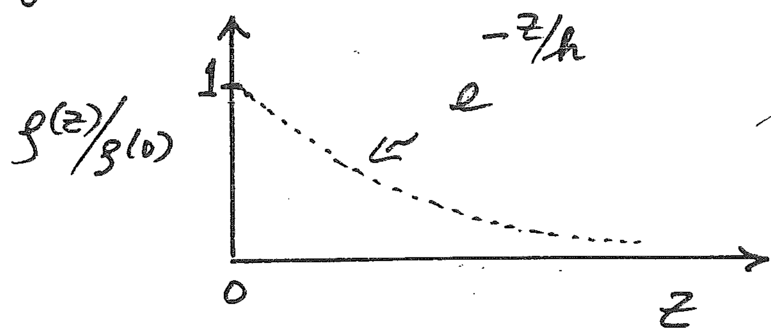
Transmission Correction

✓ Unfortunately there is not a vacuum between the air shower [light source] and the fluorescence detector [light receiver].



$$\Rightarrow I = I_0 \underbrace{e^{-x/\lambda}}_{\equiv\, T \leq 1}$$

✓ More unfortunately the scattering medium is not uniform. To first order it is uniform "horizontally" and only varies "vertically":



$h \equiv$ scale height of scattering medium

✓ For fluorescence light the main scattering processes are:

i) Rayleigh on the "molecular" atmosphere

ii) Mie on aerosols (in the atmosphere)

✓ To first order we need to know:

i) "$\rho(0)$" for the molecular and aerosol "parts" of the atmosphere ... or equivantly the attenuation lengths at fixed height ($z = 0$).

$$\downarrow$$

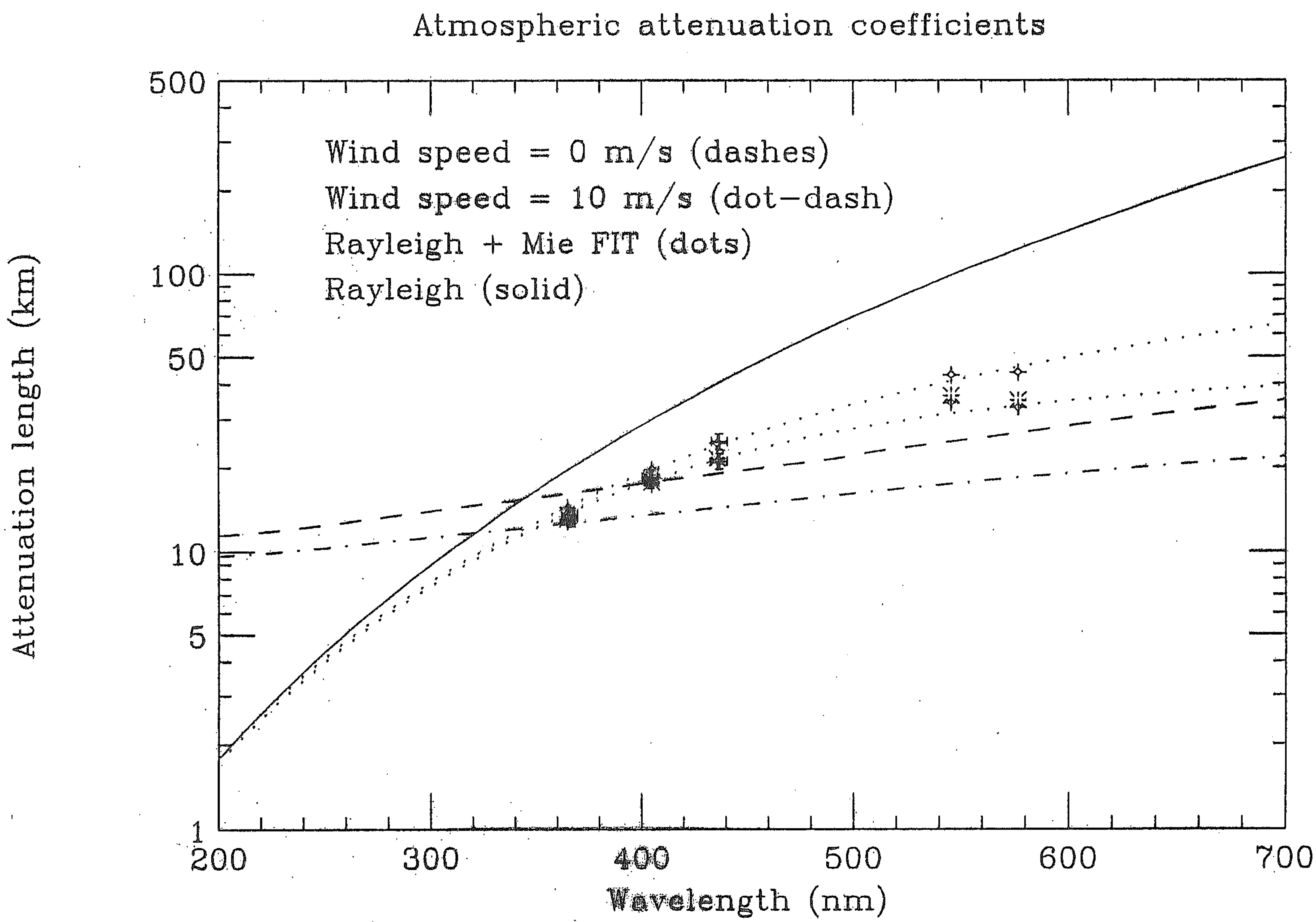
$$\Lambda^m, \Lambda^a$$

ii) "h" for the molecular and aerosol "parts" of the atmosphere

$$\downarrow$$

$$h^m, h^a$$

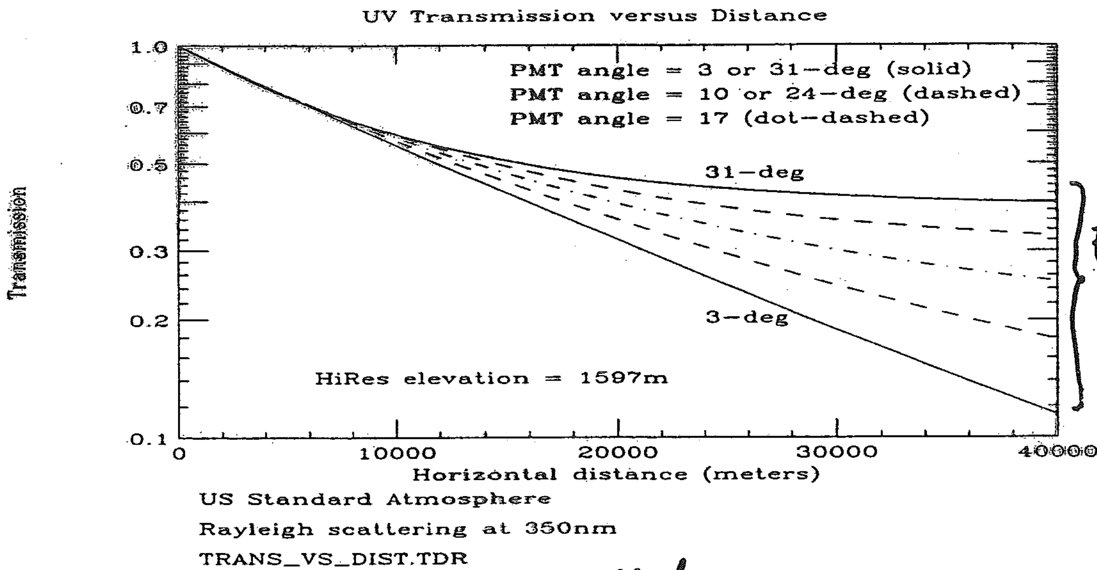
(in practice h^m implies an isothermal atmosphere which is not true below ~11 km; thus we actually use an adiabatic model for the molecular atmosphere: $T(z) = T(0) - 6.5^\circ z(\mathrm{km})$)



D. R. Longtin et al, A Wind Dependent Desert Aerosol Model

Extinction coefficient

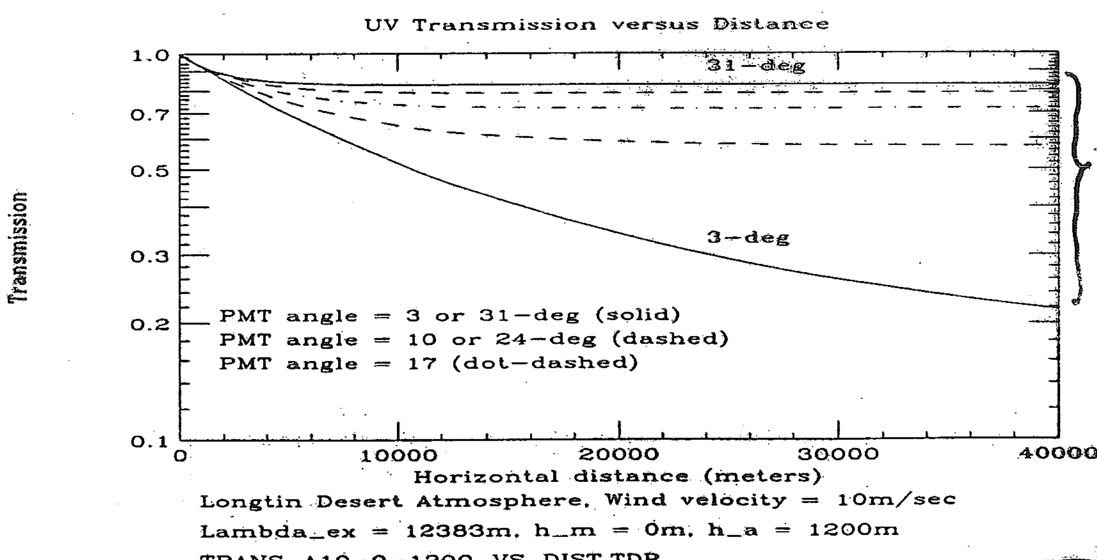
(+) Millard County measurements, June 2000



fluorescence telescope viewing angle(s)

rather well known

Fig. 2a: Transmission factor, $\boxed{T^m}$ for Rayleigh scattering in the (molecular) atmosphere. Curves are shown for HiRes viewing angles from 3° ~ 31° to the horizon.



fluorescence telescope viewing angle(s)

must be measured to limit $\delta E/E \approx \delta T^a/T^a \approx 0.1$

Fig. 2b: Transmission factor, $\boxed{T^a}$ for Mie scattering on the aerosols in the atmosphere. The aerosols are described by a (horizontal) attenuation length $\Lambda^a(350nm) = 12,383$m and an exponential scale height, $h_a = 1200$m(†) [3,4]. Curves are shown for HiRes viewing angles from 3° ~ 31° to the horizon.

(†) FOR COMPARISON:

	molecular	aerosols
Λ	~18 km	12 ~ 20 km
h	~7.5 km	~1.2 km

(Aerosol) transmission corrections depend on the vertical aerosol profile... and the normalizing ($\Lambda(0)$)!!

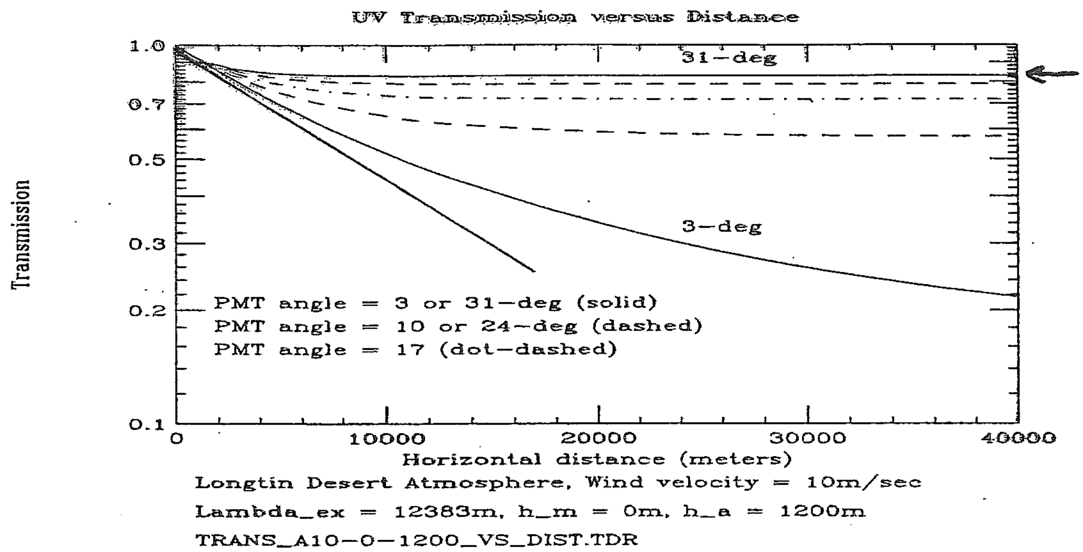
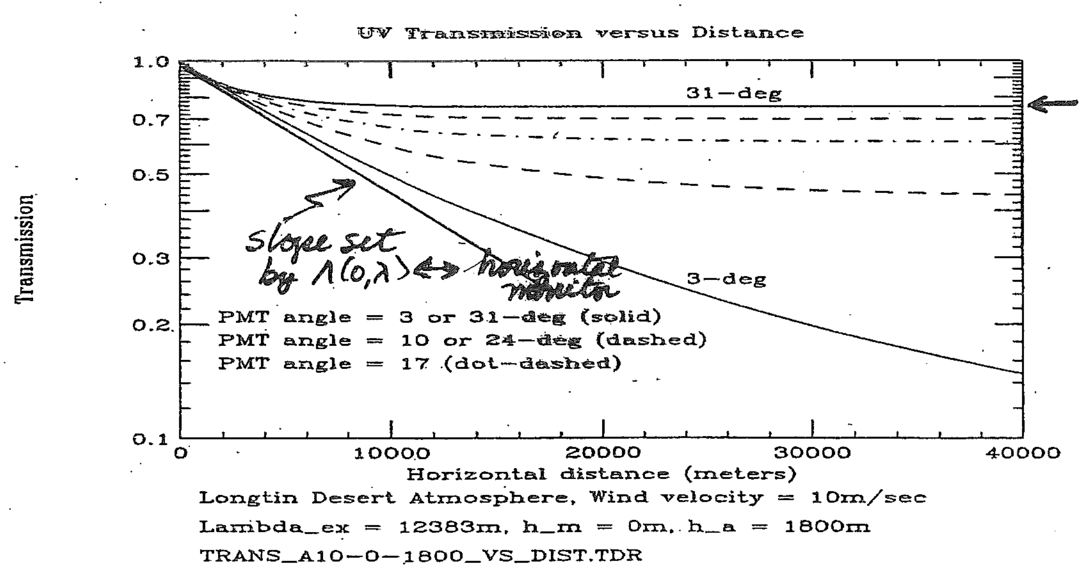


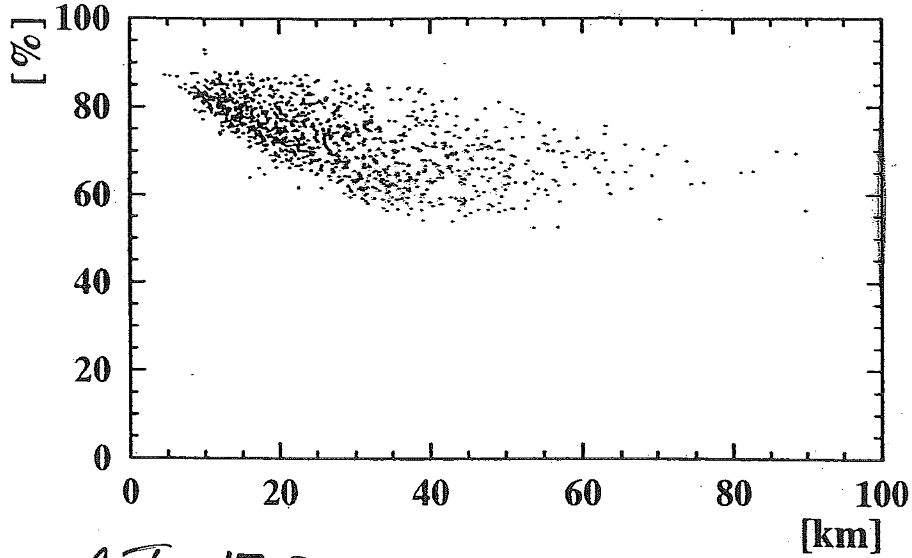
Fig. 3a': Transmission factor, T^a, for Mie scattering on the aerosols in the atmosphere. The aerosols are described by a (horizontal) attenuation length $\Lambda^a(350nm) = 12,383$m and an exponential scale height, $\underline{h_a = 1200\text{m}}$ [3,4]. Curves are shown for HiRes viewing angles from $3° \sim 31°$ to the horizon.



Related to aerosol optical depth to "infinity" (vertically)

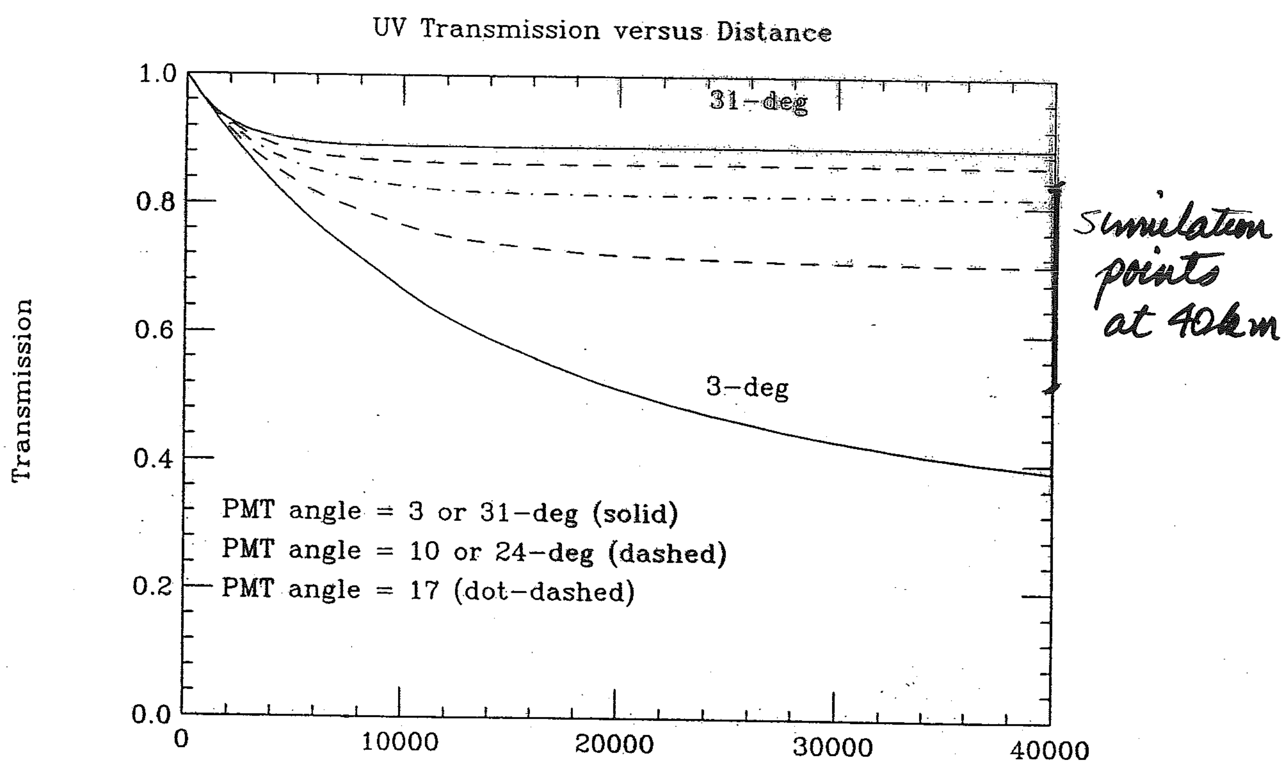
Fig. 3b': Transmission factor, T^a, for Mie scattering on the aerosols in the atmosphere. The aerosols are described by an exponential scale height, $\underline{h_a = 1800\text{m}}$ [3].

Aerosol Transmission Correction on a "Clear" Night.



T.A. Proposal Jan 17, 2000

FIG. 4.13: Scatter plot of the distance from the shower luminous center to the station vs Mie extinction. It is plotted for the nearest station to the shower center.



TA Proposal atmosphere model:

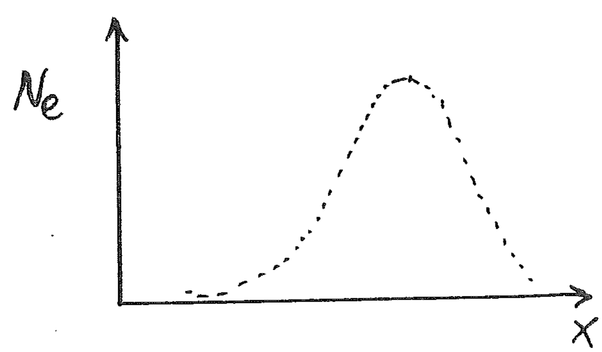
Lambda_ex = 20000m, h_m = 0m, h_a = 1200m

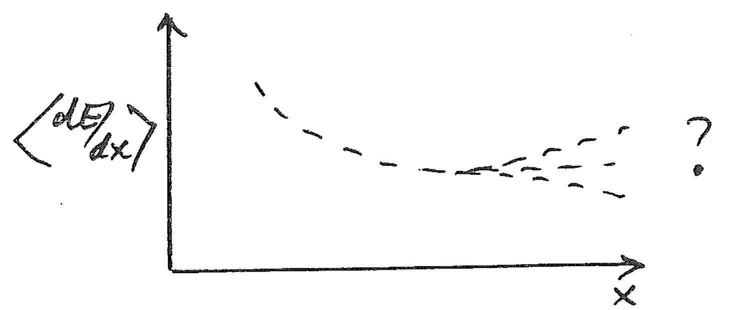
TRANS_20KM-0-1200_VS_DIST.TDR

Shower "energy integral"

✓ The "energy integral" sums up the shower energy. The $\langle dE/dx \rangle$ is "more" than collisional dE/dx of e's in air!

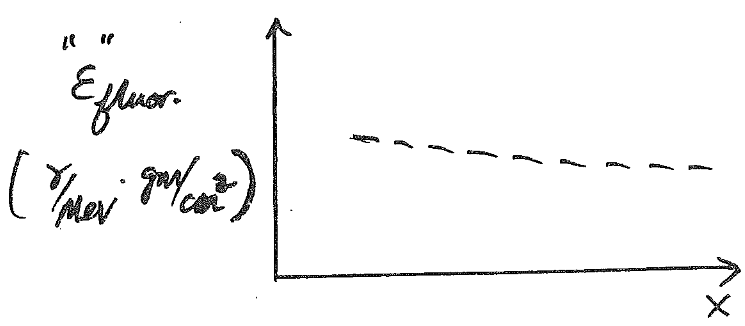
✓ The "energy integral" in the fluorescence context:





$$\left\langle \frac{dE}{dx} \right\rangle \equiv \frac{\Delta E \text{ available to air fluorescence}}{\Delta X \; N_e(X)}$$

? => ~11% of shower energy dropped even in EM showers w/o $\mu^+\mu^-$. This needs to be "included"



$$E_{TOT} = \frac{\int_0^\infty \left\langle \frac{dE}{dx} \right\rangle N_e(X)\, dX}{\mathcal{E}_{vis}} \longleftrightarrow \frac{\int_0^\infty \frac{N_{fluor\,\gamma}(X)\, dX}{\mathcal{E}_{fluor}(X)}}{\mathcal{E}_{vis}}$$

dx in /c

Shower Energy Integral

a) Rossi def^{n}: $$E_{em} = \underbrace{\frac{\varepsilon_{crit}}{X_0}}_{\equiv \langle dE/dx \rangle} \int_0^\infty \underbrace{N_e(x)\,dx}_{\text{total path length}}$$

b) CORSIKA based simulation, C. Song et al, find:

i) $\langle dE/dx \rangle \doteq 2.2\ \mathrm{MeV}/(\mathrm{gm/cm^2\ air})$

ii) $\underbrace{\varepsilon_{visible}}_{\text{corrects for shower energy} \to \nu\text{'s}, \mu\text{'s}..} \doteq 0.89$ $\quad (\sim 10^{19}\,\mathrm{eV}$ showers$)$

c) $E_{shower} \longleftrightarrow N_{max}$ relationship:

i) EM: $$E_{em} \doteq N_{max}\sqrt{2\pi}\cdot\underbrace{\sigma^{em}_{shower}}_{\sim 235\,\mathrm{gm/cm^2}\ \text{EM "theory"}}\cdot\langle dE/dx \rangle$$

$$\doteq \underline{N_{max}\cdot(1.30\ \mathrm{GeV/particle})} \longleftarrow$$

2nd lucky co-incidence

ii) Hadronic: $$E_{had} = \frac{N_{max}\sqrt{2\pi}}{\varepsilon_{visible}}\cdot\underbrace{\sigma^{had}_{shower}}_{\sim 210\,\mathrm{gm/cm^2}\ \text{Fly's Eye}}\cdot\langle dE/dx \rangle$$

$$\doteq \underline{N_{max}\cdot(1.30\ \mathrm{GeV/particle})} \longleftarrow$$

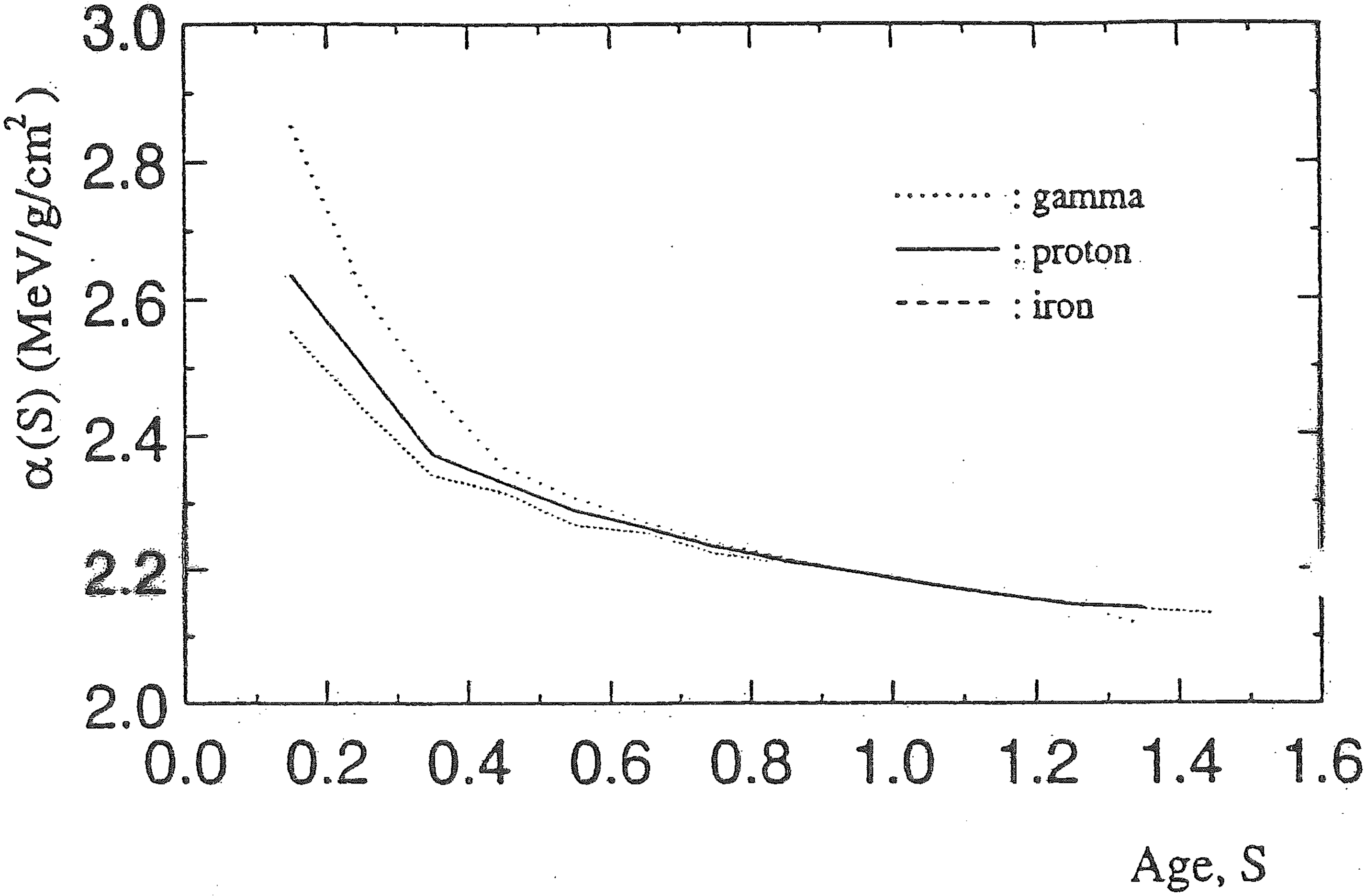


Fig. 2. The mean ionization loss rate dE/dX as function of S for γ-ray, proton, and iron-induced showers at 10^{17} eV.

C. Song, et al., astro-ph/9910195

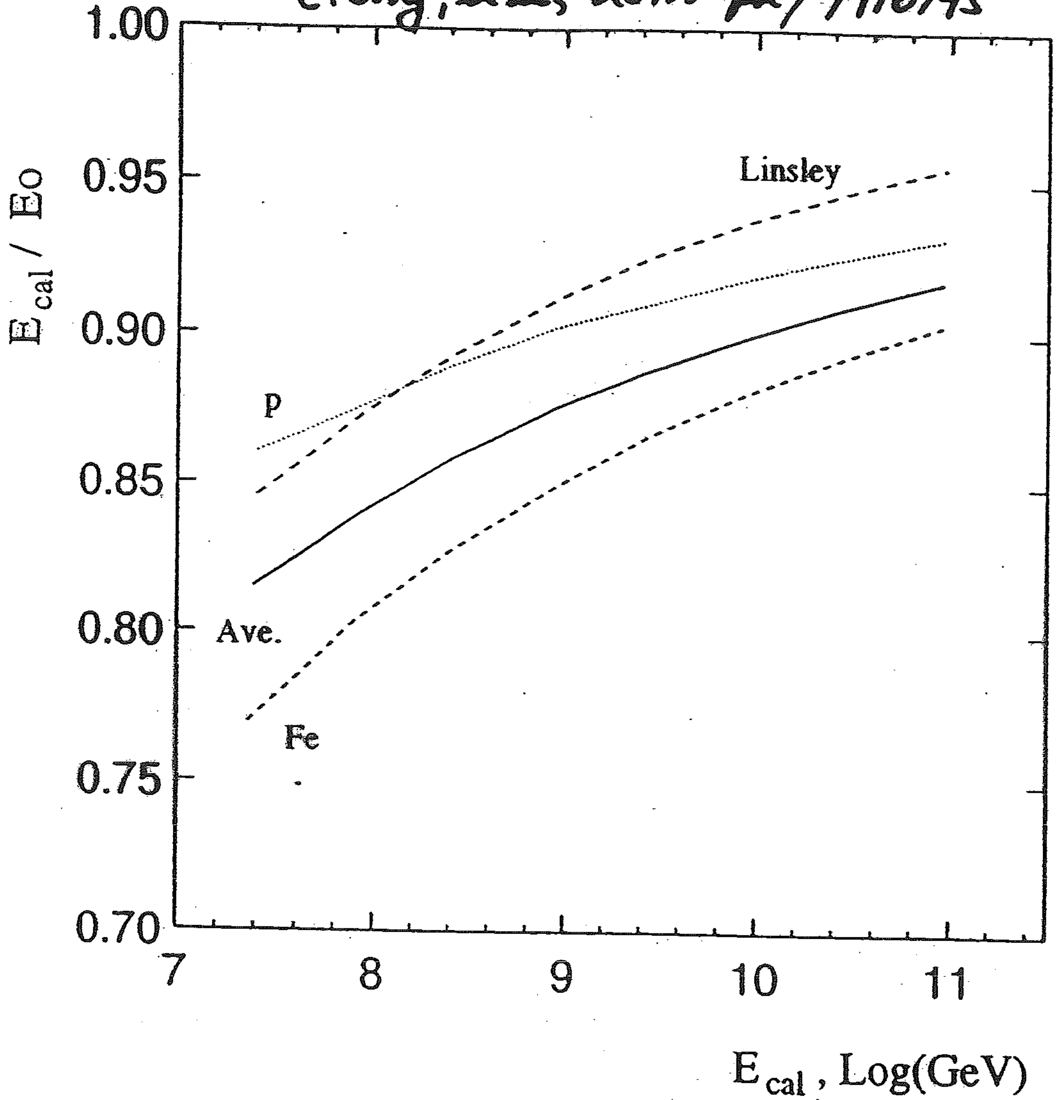


Figure 4: The functions for correcting the calorimetric energy to the primary energy, as a function of calorimetric energy. Shown are the corrections for proton showers (dotted line) and iron showers (short dashed line) and an average of the two(solid line). For comparison, Linsley's function is also shown.

... so lets do it!

✓ "fit" shower longitudinal profile to an appropriate functional form:

i) Gaussian in X :

$$N_e(X) = N_{max}\, e^{-\frac{(X-X_{MAX})^2}{2\sigma_X^2}}$$

$$E = \left\langle \frac{dE}{dX} \right\rangle N_{max} \sqrt{2\pi}\, \underline{\sigma_X} \Big/ \varepsilon_{vis}$$

"most intuitive" ... but least well describes the data

ii) Gaisser-Hillas :

(3 parameters if $\lambda = 70\,\text{gm/cm}^2$ fixed)

$$N_e(X) = N_{max} \left(\frac{X - X_0}{X_{MAX} - X_0} \right)^{\frac{X_{max}-X_0}{\lambda}} e^{\frac{X_{max}-X}{\lambda}}$$

$$E = \left\langle \frac{dE}{dx} \right\rangle N_{max}\, \underline{\lambda}\, \alpha^{-\alpha} e^{\alpha}\, \Gamma(\alpha+1) \Big/ \varepsilon_{vis}$$

where $\alpha = \frac{X_{max} - X_0}{\lambda}$

iii) Gaussian in "age" $\equiv s$:

$$N_e(s) = N_{max}\, e^{-\frac{(s-1)^2}{2\sigma_s^2}}$$

$$s = \frac{3X}{1+2X_{max}}$$

$$E \doteq \left\langle \frac{dE}{dx} \right\rangle N_{max}\, \frac{6}{4}\, \underline{X_{max}} \sqrt{2\pi}\, \sigma_s \Big/ \varepsilon_{vis}$$

"newly proposed" ... need to include "X_0" for non-traditional showers (ν's)

Q. How do these models "contribute" to fluorescence energy uncertainty?

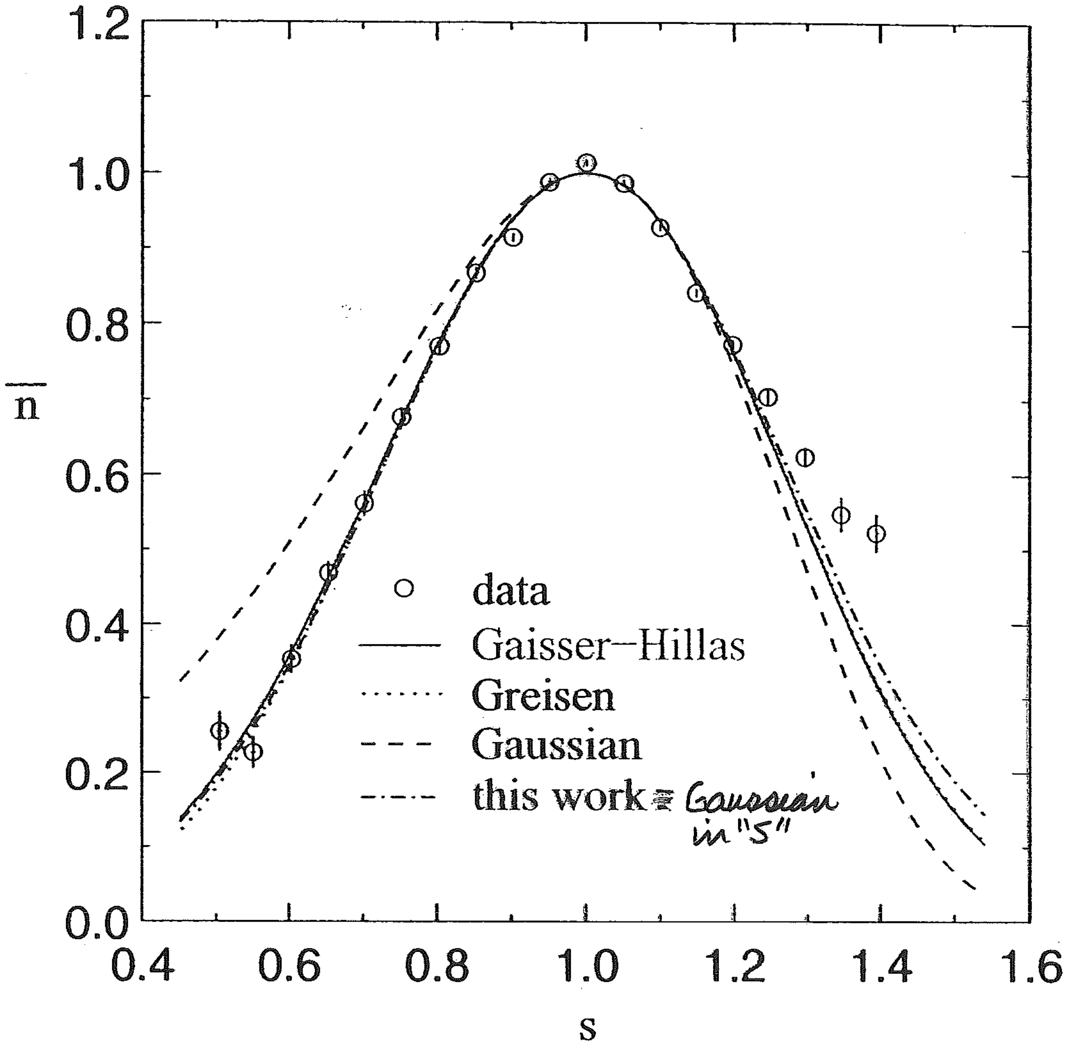


FIG. 4: Comparison between the data and test functions. Circles refer to data. The solid line refers to the G-H function, the dotted line to the Greisen function, the dashed line to the Gaussian function and the dash-dotted line to the newly proposed symmetrical Gaussian function of the shower age.

T. Abu-Zayyad et al, Oct 11/2000

fluorescence PMT "gain" measurement

- ✓ various optical calibrations of the fluorescence telescopes ... can we get one more essentially for free?

- ✓ the method is courtesy of the HiRes experiment:

$$\text{Signal}\left(\begin{smallmatrix}\text{ADC}\\ \text{value}\end{smallmatrix}\right) = \#\text{P.E.} \times \text{gain}$$

$$\text{Noise}\left(\begin{smallmatrix}\text{ADC}\\ \text{value}\end{smallmatrix}\right) = \sqrt{\#\text{P.E.}} \times \text{gain} \times f$$

Solving:

$$\boxed{\#\text{P.E.} = f^2 \times \left(\frac{\text{Signal}}{\text{Noise}}\right)^2}$$

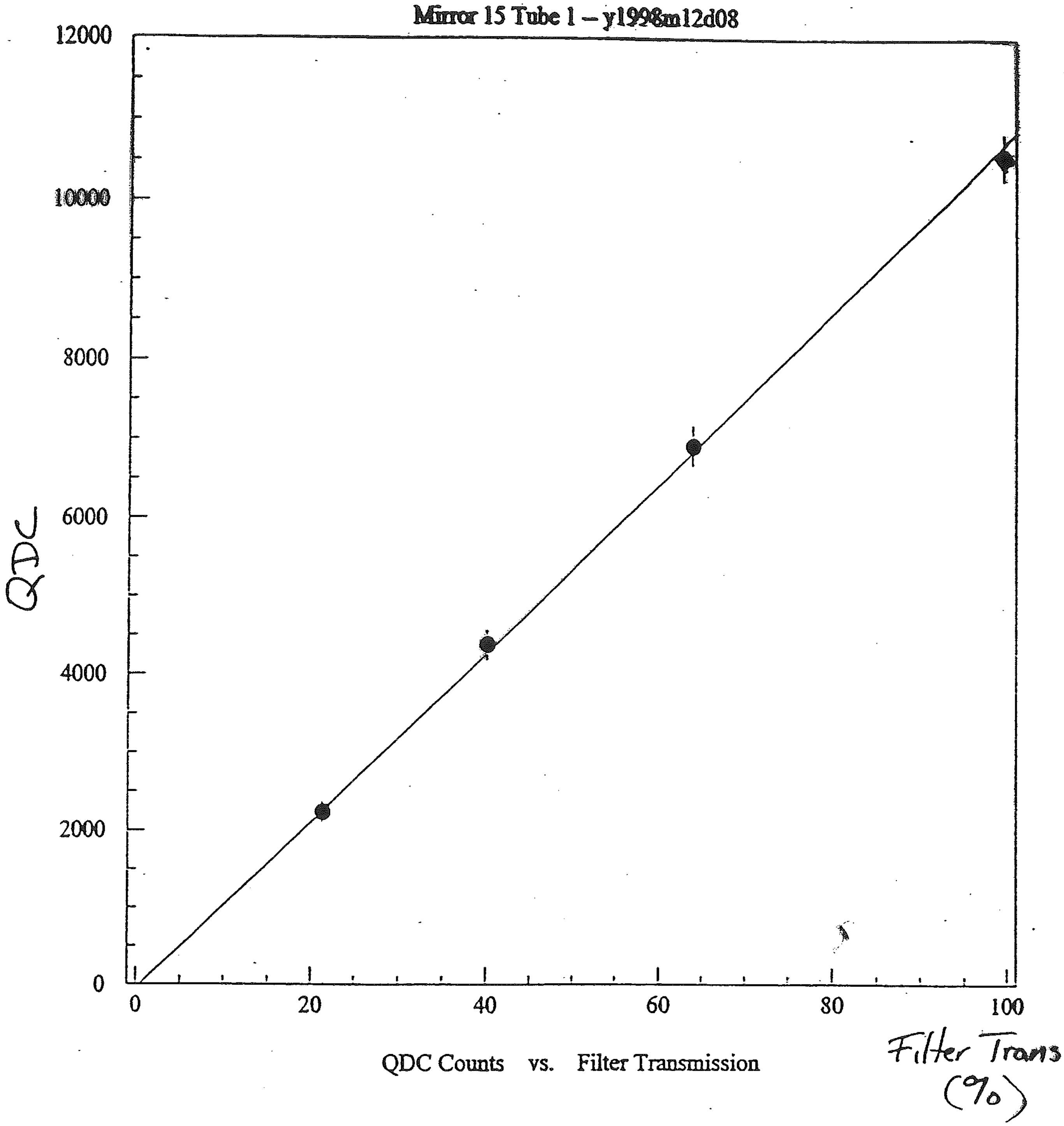
Where: f is characteristic of PMT from additional fluctuations at first dynode. This must be determined and is $\sim (1.5)^{1/2}$ for HiRes PMTs. Please measure this!

Signal is the "pedestal subtracted" value

$$\text{Noise}^2 = \text{Noise}^2_{\text{TOT}} - N_0^2$$

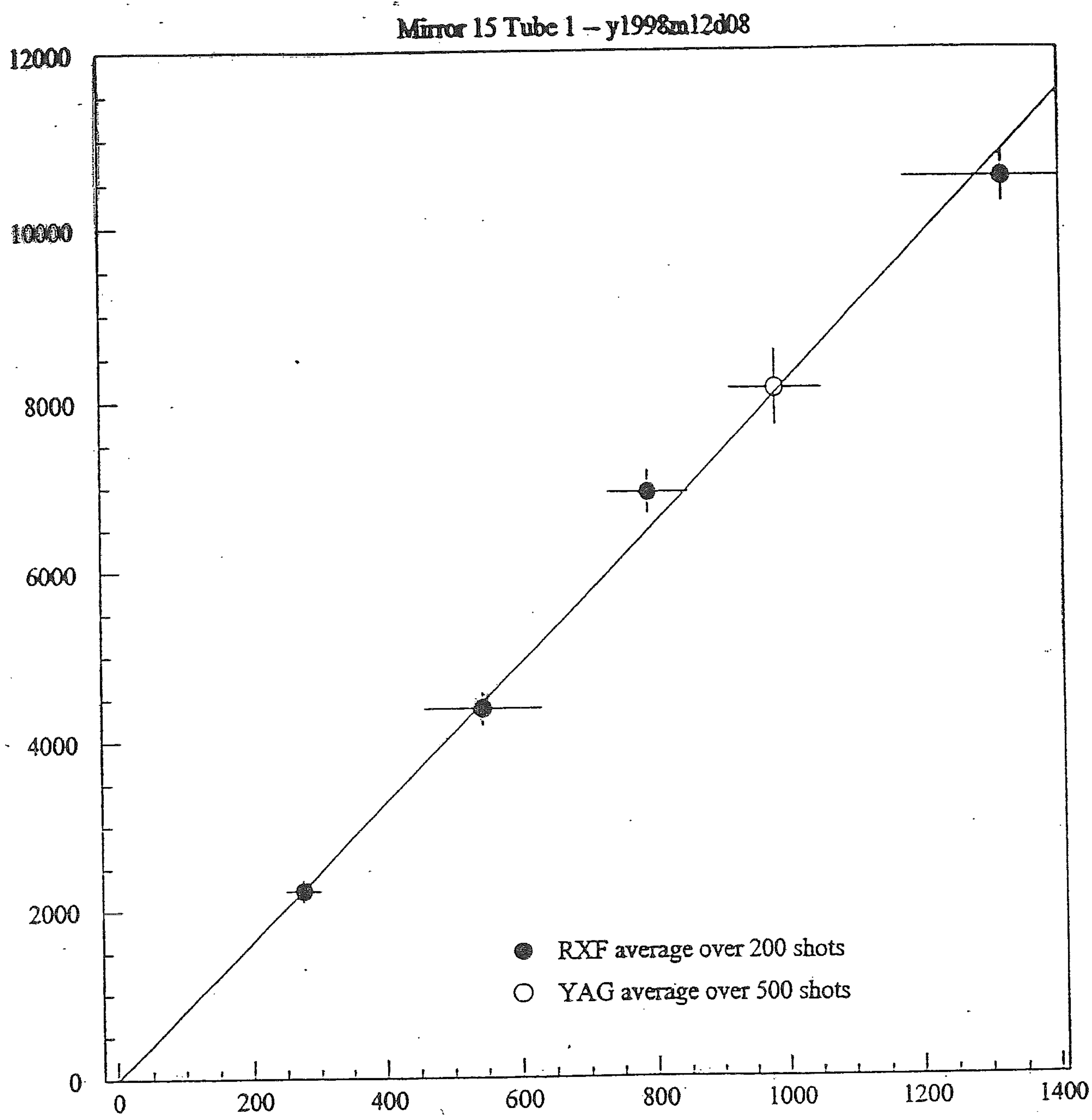
at zero signal

Finally a plot of "Signal vs #PE" is the PMT gain calibration... for free from the optical calibration system.



QDC Counts vs. Filter Transmission

Pedestal Subtracted



QDC counts vs. Number of Photoelectrons

(Y-axis is shifted so that QDC's = 0 at Pedestal) o o o so the fun is in the details

o o o and it is my view that many details need to be better understood/documented.