X-641-69-491

PREPRINT

NASA TM X-63740

ANOMALOUS COMPONENT OF ATMOSPHERIC MUONS

KAICHI MAEDA

NOVEMBER 1969

REVISED
JANUARY 1970

GSFC
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

29

X-641-69-491

ANOMALOUS COMPONENT OF ATMOSPHERIC MUONS

Kaichi Maeda

November 1969

Revised

January 1970

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

ANOMALOUS COMPONENT OF ATMOSPHERIC MUONS

Kaichi Maeda
Goddard Space Flight Center
Greenbelt, Maryland

ABSTRACT

An alternate interpretation of the recent underground muon data of Keuffel et al. is presented. This new interpretation, which does not invoke an anomalous component of atmospheric muons produced by the so-called X-process, attempts to resolve discrepancies existing between the previous and the latest Utah results, as well as those with data from the underground experiments at Kolar.

It has been well known that muons observed underground below several hundred GeV are the decay products of cosmic ray mesons produced by nuclear interactions of the primary cosmic ray particles with air nuclei in the upper atmosphere. New results of underground experiments reported recently by Keuffel et al.,[1] however, are said to confirm earlier indications that a fraction of the total flux of muons above around 1 TeV is produced by a different process. The existence of this new component of high energy muons has been postulated in order to explain the observed muon zenith angle distribution.

Since this new production process, if it exists, would signify important consequences in high energy physics, it is the purpose of this letter to present one possible interpretation of the latest Utah results without having to invoke a new component in the very high energy atmospheric muons.

The solid points in Fig. 1(a) give the new data (cf. Fig. 2(a) and (b) of Keuffel et al.[1]) of integral intensities of muons, $I(h,\theta)$ in $cm^{-2}\ sec^{-1}\ ster^{-1}$, at the slant depth h, with zenith angle θ, shown along the top. The data points are plotted against sec θ^*, where θ^* is the zenith angle at the production layer of muons in the atmosphere for a trajectory whose zenith angle at the observation point is θ. Since both scales are logarithmic, a parameter s defined by the formula

$$I(h, \theta) = I(h, 0)\ \sec^s \theta^* \tag{1}$$

may be found from the slope of a straight line drawn through the experimental points. The value of s thus determined is then plotted against slant depth h, in Fig. 1(b) (cf. Fig. 2(c) of Keuffel et al.[1]). Since the penetration depth of muons increases with the incident energy, those plotted values of s can be compared with the calculated energy dependence of s, using the range-energy relation of muons in the ground. One such curve computed by Keuffel et al.[1] is shown by the top solid line (labeled R = 0) in Fig. 1(b). In this calculation it is assumed that muons in these energy ranges are produced by the decay of cosmic ray mesons, consisting of 80% pions and 20% kaons. Three additional curves are given for comparison: the dashed line and dotted line give Maeda's results[2,3] for pion decay and kaon decay, respectively; and the dash-dot line corresponds to Osborne's all-kaon case[4]. It should be noted that in Osborne's all-kaon curve, all modes of muon production by kaon decay are considered, while Maeda's kaon curve corresponds to $K_{\mu 2}$ decay only.

Strictly speaking, the zenith angle dependence of muon intensity is not proportional to $\sec^s \theta^*$ with a constant s for a given energy, since s changes with angle even for the same depth h.[3,5] This can be seen clearly from the three theoretical curves shown in Fig. 1(a), where the dashed, dotted and dash-dot lines correspond to those in Fig. 1(b). The determination of s for these three curves was, therefore, made for $\theta^* = 60°$. The other three solid lines in Fig. 1(b) were computed by Keuffel et al.,[1] assuming a new muon production process called the X-process.[6] The parameter R is the relative amplitude of the X-process with respect to the usual muon production in the atmosphere, given by the following formula for the differential muon energy spectrum,[6]

$$M(E, \theta) = C_\pi E^{-\gamma-1} r^\gamma K(E, \theta)\, B\, (E \cos \theta^* + B)^{-1} + R\, C_\pi E^{-\gamma-1} \qquad (2)$$

where $\gamma = 1.7$, $r = 0.76$, $B = 90$ GeV, $C_\pi = 0.225$ and $K(E,\theta)$ is a factor given by Osborne.[4] $M(E, \theta)$ is in units of $cm^{-2} sec^{-1} ster^{-1} GeV^{-1}$. The first term in the right hand side of Eq. (2) corresponds to the usual atmospheric muons, and the muons corresponding to the second term can be called the <u>anomalous</u> atmospheric muons. From Fig. 1(b), the contribution of the X-process to muon production above 10^{12} eV was estimated by Keuffel et al.[1] to be of the order of 2%. They state that the advantage of this new analysis is that no measurement of the vertical intensity of muons is required. As can be seen from Fig. 1(a), however, an extrapolation of the solid line drawn through the data points to the ordinate at $\sec \theta^* = 1$ should give the vertical intensity of muons at the depth h, I(h, 0) (cf. Eq. (1)). In Fig. 2 the square points show the values of I(h, 0) thus determined for six cases of h. These new values are in good agreement with the previous Utah curve,[7] indicated by the dashed line in Fig. 2 (cf. Fig. 1 of Bergeson et al.[7]), except at h = 5430 hg/cm^2. The previous value of I(h, 0) at h = 5430 hg/cm^2, which would fall along a smooth curve of the integral spectrum, is indicated by the dashed square both in Fig. 1(a) and Fig. 2. If this value is used for the determination of the s-value at this depth, the corresponding value of s is far smaller than the one indicated by Keuffel et al.[1] This is shown by the heavy dashed error bar in Fig. 1(b). In this respect, the conclusion[1] that the X-process percentage, i.e. the value of parameter R, goes through a broad maximum in the vicinity of 4000 hg/cm^2 is questionable.

The depth-intensity curves, $I(h, \theta)$, have been calculated for $0° \leqq \theta < 90°$, by extending the well-accepted energy spectrum of muon parents at production to higher energies.[2,3,4] The vertical intensity of muos, $I(h, 0)$, as well as the other $I(h, \theta)$-lines are, therefore, given subsequently once a curve is fitted at a certain depth h. In Fig. 1(a) Maeda's all-pion curve is used to normalize to the data at h = 2330 hg/cm^2, which seems to be most accurately determined among the six cases of reported data. The $I(h, 0)$ values thus obtained are shown in Fig. 2 by the solid line. For comparison, the depth-intensity curve of muons obtained by Hayman et al.[8] (labeled HPW) and that of Maeda[2] are also shown in Fig. 2 by the dotted line and the dash-dot line, respectively. It should be noted that Maeda's previous $I(h, 0)$-curve[2] (labeled M-I) was drawn by normalizing the calculated curve to the data points at 45° with depth range from 1800 to 3000 hg/cm^2, while the new $I(h, 0)$-curve (labeled M-II) is obtained by using the data points at the depth 2330 hg/cm^2 for the angular range from 42° to 56°. If these differences in normalization and in data are taken into account, Maeda's two curves of $I(h, 0)$ are quite consistent with each other and in very good agreement with the HPW curve, although these are somewhat lower than the median value of the world survey data.[9] For comparison, the $I(h, 0)$-curve given by Osborne[10] (which is derived from the OWP-curve) is shown as a thin line in Fig. 2.

The present new results indicate, therefore, that the Utah muon data are consistent with the vertical depth-intensity curve given by Hayman et al.[8] provided that no anomalous component of muons is assumed. It is worth-while to note that the anomalous Utah data point at 5430 hg/cm^2 shown in Fig. 2 is below the OWP-curve referred by Bergeson et al.[7], previously.

Finally, if new $I(h, 0)$ values determined in the present analysis are used for the computation of the enhancement factor $G = I_{obs}/I_{vert}$, the G-value increases significantly with angle θ^*, contrary to that shown in Fig. 4 of Keuffel et al.[1] The new G values using for values of I_{vert} the curve labeled M-II in Fig. 2, are shown as the solid circles in Fig. 3. The open circles are those given by Keuffel et al.[1] The notations for the theoretical curves correspond to those in Fig. 1 and the top scale indicates the h-value of each data point. The new G values, which are consistent with muons produced from pion- and kaon-decay only, are similar to those obtained in the underground experiments at Kolar.[11,12] This resolves the discrepancy that has existed between the results of these two experiments.

I would like to thank my colleagues in the Center, especially to Dr. G. Mead who read and corrected the manuscript with critical comments. I would also like to express my appreciation to Dr. J. L. Osborne of the University of Durham for his remarks on this short note.

References

1. J. W. Keuffel, J. L. Osborne, G. L. Bolingbroke, G. W. Mason, M. O. Larson, G. W. Lowe, J. H. Parker, R. O. Stenerson and H. E. Bergeson, Proceedings of the Eleventh International Conference on Cosmic Rays (Paper MU-31), Budapest, Hungary, August 1969.

2. K. Maeda, Proceedings of the Eleventh International Conference on Cosmic Rays (Paper MU-49), Budapest, Hungary, August 1969.

3. K. Maeda, Ibid. (Paper MU-48), 1969.

4. J. L. Osborne, Thesis, University of Durham, 1966 (Unpublished).

5. K. Maeda, J. Geophys. Res. 69, 1725 (1964).

6. H. E. Bergeson, J. W. Keuffel, M. O. Larson, G. W. Mason and J. L. Osborne, Phys. Rev. Letters 21, 1089 (1968).

7. H. E. Bergeson, J. W. Keuffel, M. O. Larson, E. R. Martin and G. W. Mason, Phys. Rev. Letters 19, 1487 (1967).

8. P. J. Hayman, N. S. Palmer, and A. W. Wolfendale, Proc. Roy. Soc., 275A, 391 (1963).

9. M. G. K. Menon and P. V. Ramana Murthy, Progress in Cosmic Ray and Elementary Particle Physics (North Holland Publishing Co., Amsterdam, 1967), Vol. 9.

10. J. L. Osborne, private communication; J. L. Osborne, A. W. Wolfendale and N. S. Palmer, Proc. Phys. Soc. 84, 911 (1964).

11. M. R. Krishnaswamy, M. G. K. Menon, V. S. Narasimham, S. Kawakami, S. Kino and S. Miyake, Phys. Letters 27B, 535 (1968).

12. S. Miyake, private communication. Results shown in Fig. 3 of Krishnaswamy et al.[9] have been corrected for the new depth measurements, leading to a good agreement with the present results.

Figure Captions

Figure 1. Muon intensities vs sec θ^* at constant h. The solid line segments have been fitted to the data points shown by solid circles (cf. Fig. 2(a),(b) of Keuffel et al.[1]), the resulting slopes s are summarized in the right hand side together with s-value lines predicted for various values of R (cf. Fig. 2(c) of Keuffel et al.[1]). The dashed lines and the dotted lines show Maeda's results for pion-decay and kaon-decay, respectively, and the dash-dot lines show Osborne's all-kaon case. The scale on the top of (a) is the zenith angle θ at the observation point, corresponding to the values of sec θ^* given on the bottom.

Figure 2. The vertical intensity of muons vs depth h. Squares indicate I(h, 0)-values determined by extrapolating the straight line segments in Fig. 1(a) given by Keuffel et al.[1] The dashed line is the previous I(h, 0)-curve (cf. Fig. 1 of Bergeson et al.[7]). The dotted and thin lines are vertical depth-intensity curves given by Hayman et al.[8] (labeled HPW) and Osborne et al.[10] (labeled OWP), respectively. The dash-dot line (labeled M-I) and the solid line (M-II) give results of Maeda[2] and those of the present analysis, respectively.

Figure 3. Comparison of the enhancement factor G given by Keuffel et al.[1] (open circles) and those obtained by the present analysis (solid circles). Solid lines are those given by Keuffel et al.,[1] which indicate predicted values of G with various values of parameter R, and the dash-dot line is that of Osborne's all-kaon case. The dashed line and the dotted line show Maeda's results[3,5] for pion-decay and kaon-decay, respectively.

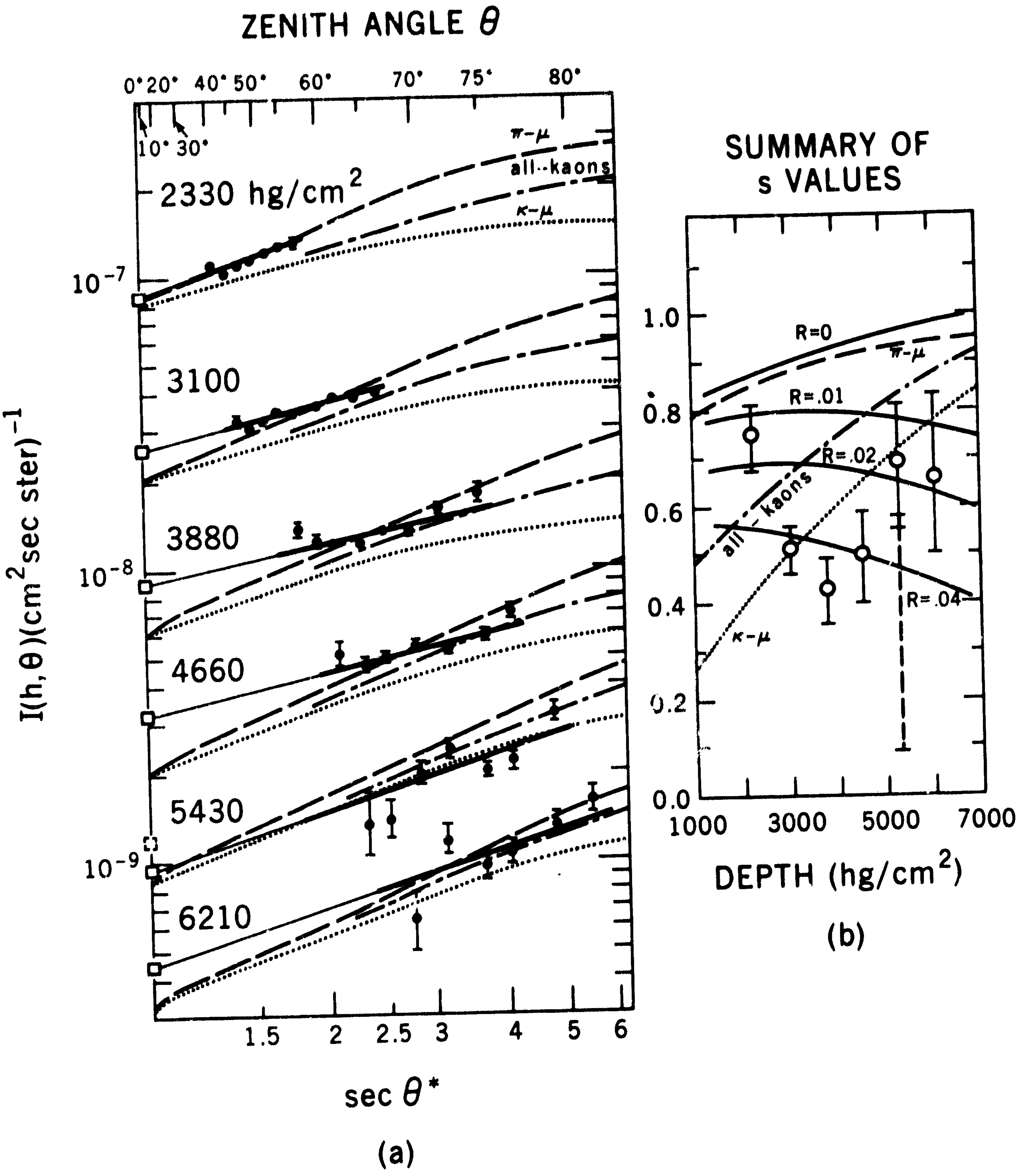
ZENITH ANGLE θ
0° 20° 40° 50° 60° 70° 75° 80°
10° 30°
π-μ
all-kaons
κ-μ
2330 hg/cm²
3100
3880
4660
5430
6210
10⁻⁷
10⁻⁸
10⁻⁹
I(h,θ)(cm²sec ster)⁻¹
1.5 2 2.5 3 4 5 6
sec θ*
(a)
SUMMARY OF
s VALUES
R=0
π-μ
R=.01
R=.02
all-kaons
R=.04
κ-μ
1.0
0.8
0.6
0.4
0.2
0.0
1000 3000 5000 7000
DEPTH (hg/cm²)
(b)

Figure I

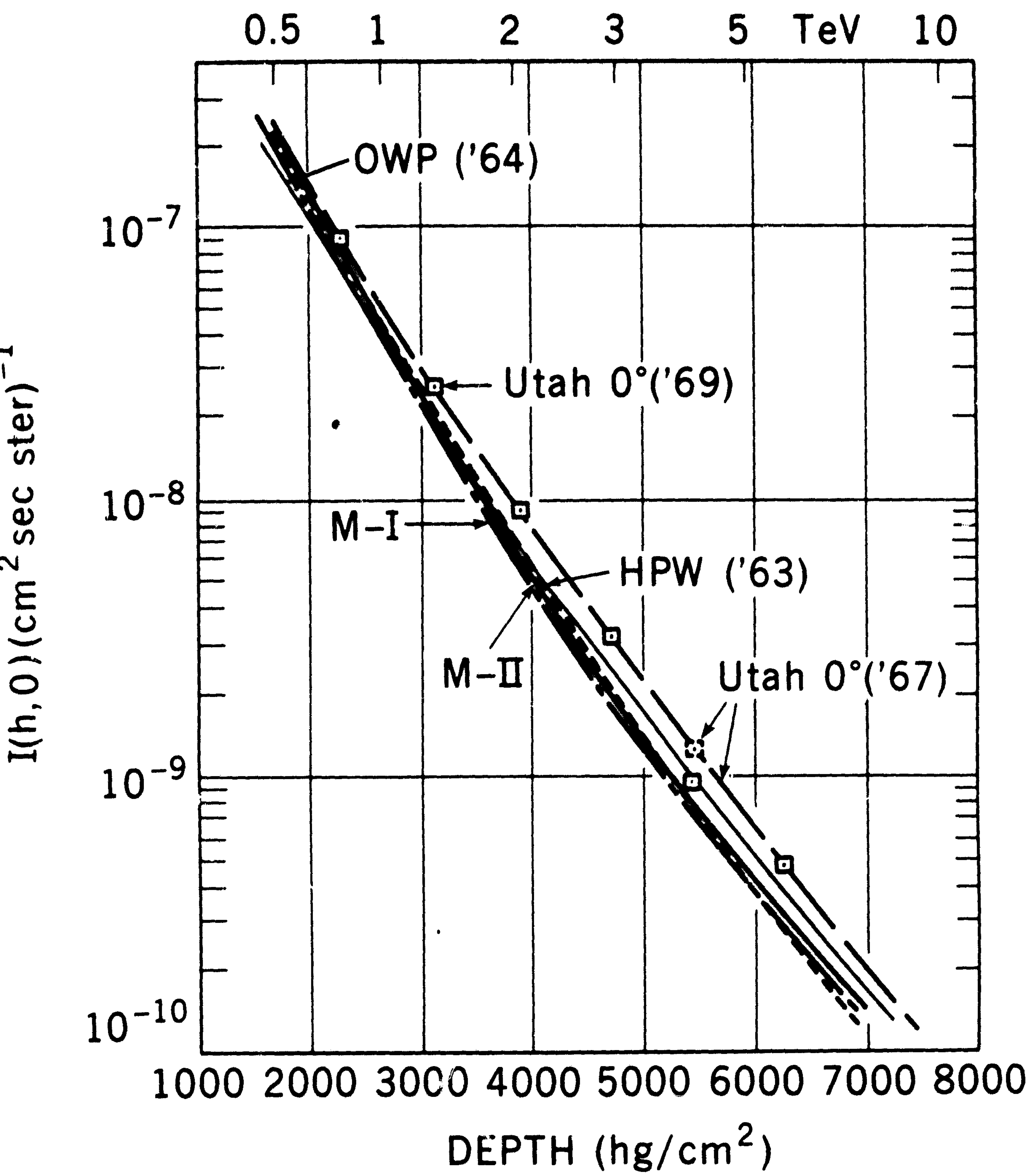
0.5
1
2
3
5
TeV
10
OWP ('64)
Utah 0°('69)
M–I
HPW ('63)
M–II
Utah 0°('67)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$I(h,0)(cm^2 sec ster)^{-1}$
1000
2000
3000
4000
5000
6000
7000
8000
DEPTH (hg/cm^2)

Figure 2

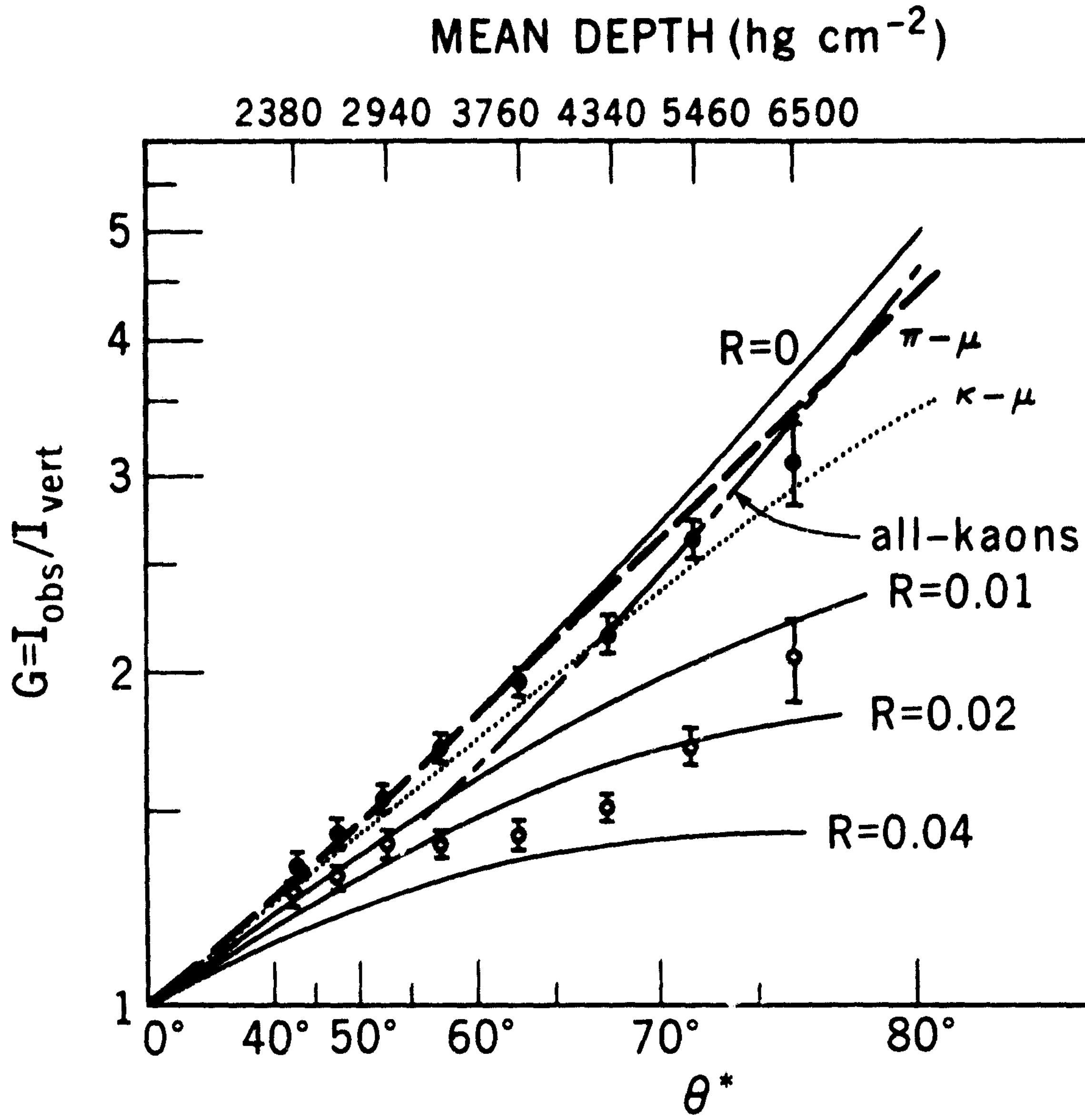
MEAN DEPTH (hg cm^{-2})
2380 2940 3760 4340 5460 6500
$G=I_{obs}/I_{vert}$
1
2
3
4
5
R=0
$\pi-\mu$
$\kappa-\mu$
all-kaons
R=0.01
R=0.02
R=0.04
0°
40°
50°
60°
70°
80°
θ^*

Figure 3