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K. Sinha
Uttar Pradesh State Observatory
Manora Peak
Naini Tal
U. P. 263 129, India

MOLECULAR ABUNDANCES IN SUNSPOTS

V. P. Gaur, M. C. Pande, B. M. Tripathi, Uttar Pradesh State Observatory, Naini Tal, India

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The results of the dissociation equilibrium calculations for Zwaan's sunspot model are given. It appears that many di- and tri-atomic molecules form in sufficient abundances in the spots. It is suggested that for assessing the differences between the physical conditions of various sunspot models the locations of various molecules on the average geometrical depth of formation versus temperature (at that depth) curve can serve as a theoretical criterion.

Содержание молекул в солнечных пятнах

Даются результаты вычисления диссоциативного равновесия для модели солнечного пятна, которую предложил Зваан. Оказывается, что многие двух- и трехатомные молекулы образуются в пятнах в достаточном количестве. Предлагается в качестве теоретического критерия для оценки разностей физических условий в разных моделях солнечных пятен использовать появление различных молекул на кривой геометрическая глубина образования — температура на этой глубине.

1. Introduction

Following earlier work on molecular abundances in the solar photosphere and in faculae (Pande et al., 1969a, b), the present investigation reports on the molecular abundances in sunspots based on Zwaan's (1965) sunspot model (hereinafter abbreviated as ZSM).

The possibility of triatomic molecular formation in sunspots is also investigated here. The presence of H₂O in sunspot spectrum has recently been reported (Wöhl, 1969; Mallia and Blackwell, 1970; Mallia et al., 1970) so a search for other triatomic molecules in sunspot spectrum may be desirable. We think that the dissociation equilibrium calculations may also help in picking up more abundant triatomic molecular species for identification. For these reasons, a number of triatomic molecular species were also included in our calculations of molecular abundances in ZSM.

2. The Calculations of Molecular Abundances in ZSM

In all about one hundred atomic, molecular and other species were included in the present calculations. Besides the species listed by Pande et al. (1969a), the following additional species were also considered:

Ti, Ti⁺, TiO, TiO₂, Sr, Sr⁺, SrH, SrO, Y, Y⁺, YO, V, V⁺, VO, CaH, BN, H₂O, HO₂, H₂S, HCO, HCN, HNO, C₃, CO₂, C₂H, CH₂, CH₃, CH₄, O₃, N₃, N₂O, NO₂, NH₃, SiC₂, Al₂O, AlCl₂ and ZrO₂.

The sources from which the dissociation and other constants were borrowed are: H₂⁺ (Vardya, 1961), CaH, TiO₂, SrO and SrH (Tsuji, 1964) and for other species Glushko et al. (1962) and Tatum's (1966) tables.

The references from which the solar elemental abundances were borrowed are: Cl (Lambert and Mallia, 1968), V (Warner, 1968), Sr (Lambert and

Warner, 1968), B (Grevesse, 1968), Br and I (Aller, 1961), F (Hall and Noyes, 1969) and for rest of the elements (Muller, 1967). A He/H ratio of 0.16 (Zwaan, 1965) has been adopted (cf. Table 1).

Table 1

Reduced equations and solar abundances for various elements

Sl. No.	Element	Abundance log N	Species included in the reduced equations
1	H	12	H, H ₂
2	C	8.62	C, CO
3	N	7.88	N, NO, N ₂
4	O	8.86	O, CO, OH
5	Si	7.45	Si, Si ⁺ , SiO
6	Mg	7.36	Mg, Mg ⁺ , MgH, MgO
7	Al	6.20	Al, Al ⁺ , AlCl
8	S	7.30	S, S ⁺ , SH
9	B	2.80	B, B ⁺ , BO
10	P	5.34	P, P ⁺ , PH
11	Be	2.34	Be, Be ⁺ , BeH, BeO
12	Li	1.54	Li, Li ⁺
13	I*	1.35	I, I ⁺ , HI
14	Br*	2.65	Br, Br ⁺ , HBr
15	Cl	5.65	Cl, Cl ⁺ , HCl
16	F	4.56	F, F ⁺ , HF
17	Zr	2.65	Zr, Zr ⁺ , ZrO
18	Ca	6.04	Ca, Ca ⁺
19	Na	6.30	Na, Na ⁺ , NaH
20	K	4.70	K, K ⁺
21	Ti	4.58	Ti, Ti ⁺ , TiO
22	Sr	2.82	Sr, Sr ⁺ , SrH, SrO
23	Y	3.2	Y, Y ⁺ , YO
24	V	3.92	V, V ⁺ , VO
25	Sc	3.04	Sc, Sc ⁺ , ScO

* As valid for the solar system.

The reduced equations in Table 1 were obtained in a manner similar to that used by us in the photospheric case (Pande et al., 1969a). These equations show the minimum number of terms needed to describe the free partial pressure of a considered element as a function of depth in ZSM.

The partial pressures thus obtained were used to calculate the required molecular concentrations at various geometrical depths in ZSM. Then, for a given molecule, the total number I per cm² in a column above optical depth $\tau(5000 \text{ \AA}) = 2.73$ and the average depth of formation \bar{Z} were calculated in the manner described earlier (cf. Pande et al., 1969b).

The results are summarised in Table 2 and Fig. 1 both of which include only those species whose I exceeds, is equal to or less by an order of magnitude than the I of CaH. In column two of Table 2 species

which are definitely known to be present in sunspots (Broida and Moore, 1957; Moore, 1964; Wöhl, 1970; Hall and Noyes, 1970) are asterisked. Table 2 shows that CaH and ZrO are the least abundant species amongst the asterisked. For this reason, I for CaH was accepted as a criterion for limiting the molecular species to relatively abundant ones only.

Table 2

Results of the dissociation equilibrium calculations for ZSM

Sl. No.	Molecule	log I	\bar{Z} Km	$T(\bar{Z})$
1	VO	14.64	43.5	3277 K
2	TiO*	15.97	45.8	3288
3	CaO	15.19	47.6	3294
4	YO	16.11	52.6	3320
5	PO	16.33	56.5	3338
6	AlO	15.11	61.2	3359
7	H ₂ O*	20.28	62.7	3365
8	CO ₂	16.70	69.6	3398
9	SO	16.76	71.0	3405
10	BO	15.17	74.9	3424
11	H ₂ S	16.94	81.3	3462
12	ZrO*	14.90	81.4	3465
13	O ₂	16.93	81.8	3467
14	MgO*	16.30	83.9	3475
15	S ₂	15.16	84.5	3480
16	HCl	17.68	84.7	3483
17	OH*	20.58	86.1	3490
18	H ₂	23.88	86.2	3495
19	CaH*	15.35	87.5	3500
20	NaH	14.92	89.3	3508
21	SiO	19.78	90.3	3517
22	AlH*	16.37	91.2	3522
23	TiO ₂	15.18	94.5	3538
24	PN	15.72	95.1	3547
25	SH	18.63	97.1	3560
26	N ₂	20.20	101.9	3588
27	HF*	17.19	104.5	3605
28	NH ₃	15.07	105.0	3608
29	NO	17.90	106.2	3615
30	PH	16.31	107.7	3622
31	MgH*	17.94	115.6	3672
32	CO*	21.38	116.0	3675
33	NS	15.09	117.6	3683
34	NH ₂	16.55	122.5	3713
35	HCO	16.90	130.7	3773
36	SiH*	18.06	139.9	3835
37	NH*	18.47	144.8	3880
38	HCN	16.30	146.2	3892
39	CH ₂	16.51	152.3	3957
40	CS	16.37	153.0	3970
41	CN*	17.90	184.3	5015
42	CH*	18.11	205.0	5910
43	C ₂ *	16.15	206.8	5985

* These are the definitely present species in sunspots (except C₂ and ZrO whose presence is now questionable).

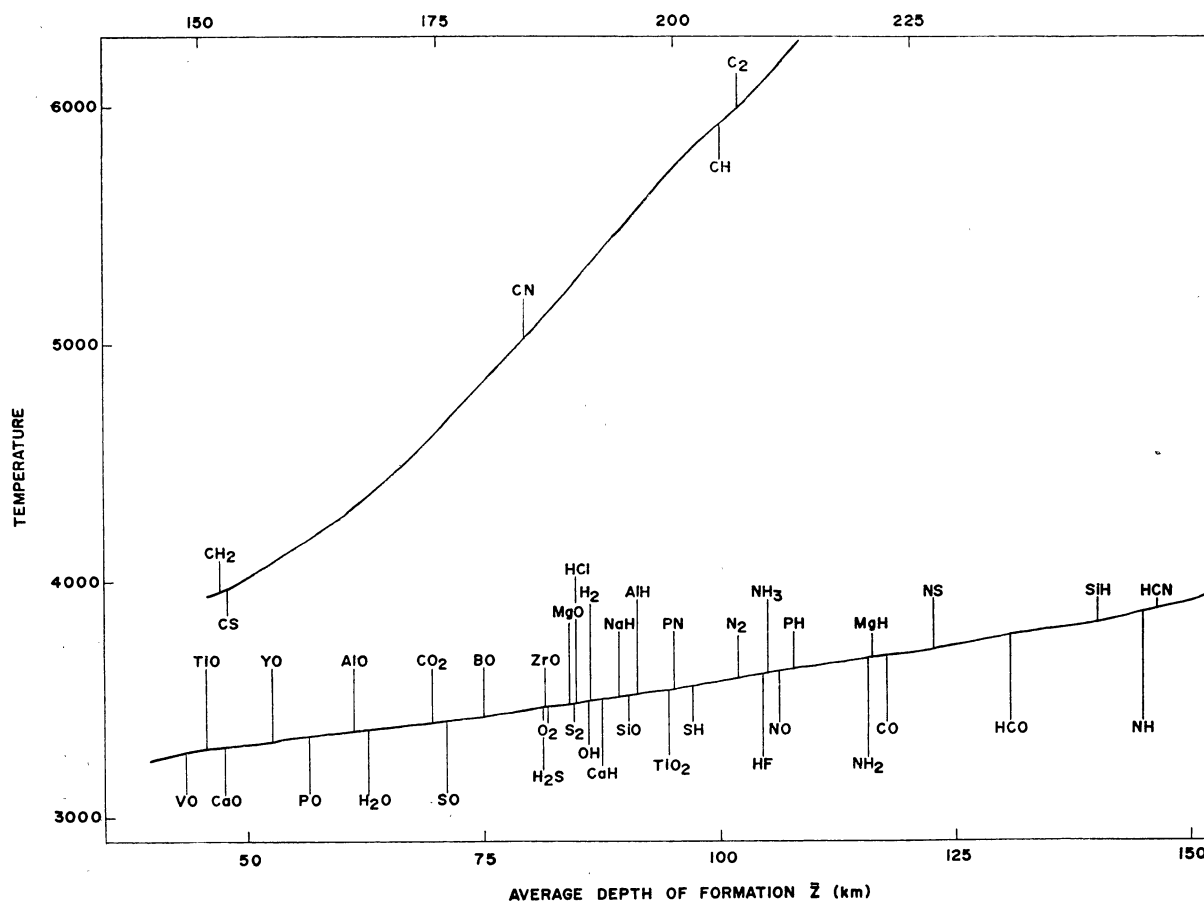
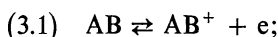


Fig. 1. The average geometrical depth of formation \bar{Z} versus the temperature T at that depth in ZSM for various abundant species.

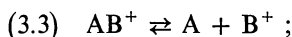
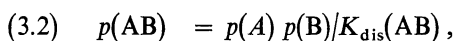
3. Discussions

Table 2 shows that several diatomic and triatomic molecular species, with I comparable to or greater than the I of CaH, form in sunspots as per ZSM. Some fairly abundant species, for which $1 < \log I(\text{CaH}) - \log I(\text{species}) < 2$, not included in Table 2, are:

H_2^+ , BH, BeH, HNO, HO_2 , ScO, SO_2 , SiC, SiN, HBr, OH^- , CP, C_2H , CH_3 , CO^+ , NO^+ , PS, MgF, AlF and SiF. The equilibrium abundances of molecular ionic species, the OH^- ion and of triatomic molecules were obtained with some restrictions. For positive ionic species AB^+ (like CO^+ , NO^+ , O_2^+ , N_2^+ and OH^+) only the process of the type $\text{AB} \rightleftharpoons \text{AB}^+ + e$ i. e. the ionisation equilibrium of the considered molecule, was used; for H_2^+ the dissociation equilibrium process $\text{H} + \text{H}^+ \rightleftharpoons \text{H}_2^+$ or a process of the type $\text{A} + \text{B}^+ \rightleftharpoons \text{AB}^+$ was used. To make an estimate of the relative contribution to the partial pressure of AB^+ by the two processes mentioned above, one needs to use the following set of reactions:



$$p_1(\text{AB}^+) = p(\text{AB}) K_{\text{ion}}(\text{AB})/p(e),$$



$$p_2(\text{AB}^+) = p(\text{A}) p(\text{B}^+)/K_{\text{dis}}(\text{AB}^+),$$

and

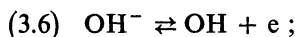
$$(3.4) \quad p(\text{B}^+) = p(\text{B}) K_{\text{ion}}(\text{B})/p(e).$$

Here, p 's denote the respective partial pressures and K 's denote the various equilibrium constants (with subscript dis and ion denoting dissociation and ionization respectively). These equations result in the ratio α of partial pressure $p_1(\text{AB}^+)$ contributed by the ionization equilibrium of AB^+ and $p_2(\text{AB}^+)$ by the dissociation equilibrium of AB^+ as follows:

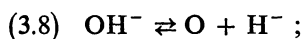
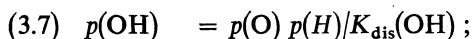
$$(3.5) \quad \alpha = p_1(\text{AB}^+)/p_2(\text{AB}^+) = K_{\text{ion}}(\text{AB}) K_{\text{dis}}(\text{AB}^+)/K_{\text{ion}}(\text{B}) K_{\text{dis}}(\text{AB}).$$

In case of OH^- we used the reaction $\text{OH} + e \rightleftharpoons \text{OH}^-$. The process $\text{O} + \text{H}^- \rightleftharpoons \text{OH}^-$ may also

operate, consequently, the following sets of reactions will account for the contribution of both the processes:

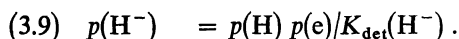


$$p_1(\text{OH}^-) = p(\text{OH}) p(e)/K_1(\text{OH}^-),$$



$$p_2(\text{OH}^-) = p(\text{O}) p(\text{H}^-)/K_2(\text{OH}^-),$$

and



Here, $K_1(\text{OH}^-)$, $K_2(\text{OH}^-)$ and $K_{\text{det}}(\text{H}^-)$ are the respective detachment constants and $K_{\text{dis}}(\text{OH})$ is the dissociation constant of OH. The relative contribution of the two processes (3.6) and (3.8) is expressed by the ratio β which results from the above equations:

$$(3.10) \quad \beta = p_1(\text{OH}^-)/p_2(\text{OH}^-) = \\ = K_{\text{det}}(\text{H}^-) K_2(\text{OH}^-)/K_{\text{dis}}(\text{OH}) K_1(\text{OH}^-).$$

Thus, the two quantities α and β , independent of electron pressure, enable us to judge the extent to which our calculations are affected if the processes ignored by us in calculating the abundances of ionic molecular species are also incorporated. Using the necessary constants from Glushko et al. (1962) we obtained α for CO^+ , NO^+ , O_2^+ , N_2^+ and OH^+ for temperatures 3000, 5000, 10 000 and 20 000 K. At all these temperatures the resulting values are equal to unity for all species excepting OH^+ . For OH^+ the $\log \alpha$ values are respectively $\bar{1}.9316$, $\bar{1}.9385$, $\bar{1}.9435$ and 0.0323 for temperatures 3000, 5000, 10 000 and 20 000 K. The β value for OH^- is also equal to unity for temperatures 3000 and 5000 K. Hence, for all practical purposes α and β can be taken to be unity for all temperatures in ZSM. This means that in ZSM, for species of type AB^+ , two processes contributing equally to the partial pressure of AB^+ operate under LTE. So to account for the processes ($\text{A} + \text{B}^+ \rightleftharpoons \text{AB}^+$ and $\text{AB} \rightleftharpoons \text{AB}^+ + e$) we have just to double the partial pressure of AB^+ at any depth as obtained on the basis of a single process. The same holds for OH^- also, because here also two processes operate contributing equally to the partial pressure of OH^- .

The diatomic and triatomic molecular abundances should be accepted with one restriction, viz., processes of the type $\text{AB} + \text{C} \rightleftharpoons \text{AC} + \text{B}$, $\text{AC} + \text{BD} \rightleftharpoons \text{AB} + \text{CD}$, $\text{AB} + \text{C} \rightleftharpoons \text{ABC}$ and $\text{AB} + \text{CD} \rightleftharpoons \text{ABC} + \text{D}$, affecting the diatomic and triatomic I values, may also operate. To include all these processes

in such calculations, it is necessary to have dissociation constants at various temperatures for all the possible processes. As not all the constants were available to us, so we have ignored the processes $\text{AB} + \text{C} \rightleftharpoons \text{AC} + \text{B}$, $\text{AB} + \text{CD} \rightleftharpoons \text{AC} + \text{BD}$, $\text{AB} + \text{C} \rightleftharpoons \text{ABC}$ and $\text{AB} + \text{CD} \rightleftharpoons \text{ABC} + \text{D}$. In short, only the processes $\text{A} + \text{B} \rightleftharpoons \text{AB}$ and $\text{A} + \text{B} + \text{C} \rightleftharpoons \text{ABC}$ have been considered.

Due to the non-availability of the dissociation constants of the two recently observed molecules in sunspot spectrum viz., CoH and NiH (Wöhl, 1970), these were not included in our calculations. Further, the difference $\log I(\text{CaH}) - \log I(\text{C}_3) > 3$ suggests that the abundance of C_3 in sunspots is low. The controversy about the presence of C_3 (Broida and Moore, 1957; Moore, 1964) may also be explained by the low abundance of C_3 .

Recently, Wöhl (1971) defining a W -index made an attempt to identify a number of molecular species in the sunspot spectrum in the region 4000–8000 Å, without considering in detail the dissociations equilibrium of molecules in the spots. If other bands of the same species occur in other spectral regions then the strongest band should be selected for W -index investigation before the presence or absence of a molecular species is accepted. For example, in case of ZrO the W -index helped in excluding its presence in sunspots (Wöhl, 1971; cf. also Webber, 1971) while earlier Moore (1964) took ZrO as definitely present in the sunspot spectrum. In contrast, the conclusion about the absence of HCl (Wöhl, 1971) can be questioned on the grounds that the investigated 5-0 band is not the strongest band of HCl. The ratio of square of matrix elements $|R(5-0)|^2/|R(1-0)|^2$ is of the order of 10^{-7} and thus, 1-0 band will be much intense (Penner, 1959). Consequently, a determination of the W -index for 1-0 band of HCl in sunspot spectrum near 3.46μ will allow one to exclude or include HCl as an observable molecule. Our calculations of the center to limb variations of the equivalent widths of $R(8)$ and $P(8)$ lines of 1-0 vibration-rotation band of HCl in ZSM show that HCl should be observable in sunspots as the equivalent widths at $\cos \theta = 1$ are 15 and 20 mA for $R(8)$ and $P(8)$ respectively. The details of this investigation will be published in near future (Gaur and Pande, 1972). Independently, Lambert et al. (1971) reached the same conclusion about the presence of the 1-0 band of HCl in a different sunspot model.

In our Table 2, the molecules not investigated by Wöhl (1971) and Sotirovski (1971) are:

PO, CO_2 , SO, H_2S , S_2 , TiO_2 , PN, SH, NS, NH_2 ,
HCN, CH_2 and CS.

The other fairly abundant species, not included in our Table 2 and also by Wöhl (1971) and Sotirovski (1971), are:

H_2^+ , CO^+ , NO^+ , OH^- , HO_2 , HNO , CH_3 , HBr , SiC
and PS .

We suggest that these species should be given priority in future identification programmes.

In Fig. 1, the average depth of formation \bar{Z} of various molecules are plotted against the $T(\bar{Z})$ in ZSM, and the locations of these molecules on the $\bar{Z} - T$ curve are shown. We believe that an inter-comparison of similar figures for various sunspot models, may serve as a theoretical criterion for judging the extent to which the runs of gas pressure and temperature with depth affect the dissociation equilibrium of molecular species in various models. The locations of various points in Fig. 1 result from the respective concentration-optical depth curves of different molecular species in a particular sunspot model. Consequently, the locations of the definitely present species in a figure similar to Fig. 1 will show the degree to which a given model represents the actual observational results, e. g. the predicted center to limb variations of equivalent widths and rotational temperatures for various molecular species based on some sunspot model, like the ZSM, can be compared with the observational results and corrections to the model parameters can be searched for. This approach will help in rejecting some of the sunspot models and in modifying others so as to bring them closer to observations. Thus, a more representative model can be arrived at.

Webber (1971) enumerated various criteria to be satisfied by an improved sunspot model and also pointed out the various observational and theoretical difficulties in interpreting the observed equivalent widths and rotational temperatures derived from the molecular lines (cf., Wöhl, 1970 also). A considerably serious difficulty arises in matching the observed and model rotational temperatures because the assumption about the equality of the rotational and local model temperatures is implicitly involved. In any physical situation, where a molecule like CH with a number of low lying electronic states is under consideration, the electronic states may be populated by the radiation field while the vibrational and rotational levels by collisions. Consequently, one cannot be sure whether the observed rotational temperature is necessarily the model rotational temperature at the average depth of formation of the molecular lines. Only a non-LTE approach as adopted by Khlystov (1967; 1970) for

CH and CN molecules in the solar photosphere can resolve such a difficulty.

Further, Webber (1971) finds that the derived oscillator strengths of CaH, TiO and MgH bands are unreasonably large if his proposed sunspot model is accepted. A cooler sunspot model will result in higher molecular abundances and thus smaller oscillator strengths for the same observed equivalent widths. However, it fails to explain the higher values of rotational temperatures. The cooler model is also supported by our calculations of the equivalent widths of the two first overtone CO lines, viz. R(29) and R(31) in ZSM (Gaur et al., 1971). The equivalent widths of these lines turned out to be much smaller than the observed values of Hall and Noyes (1969) in sunspots and consequently if models cooler than ZSM are accepted then the rotational temperatures of TiO, CaH and MgH need a reinterpretation along the same lines as followed by Khlystov (1967; 1970) for CH and CN molecules in the photosphere. As a sunspot model cooler by 300 K than the one proposed by Webber (1971) is not unreasonable, ZSM can still serve as a representative sunspot model till further improvements are made.

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- V. P. Gaur, M. C. Pande, B. M. Tripathi*
Uttar Pradesh State Observatory
Manora Peak
Naini Tal
U. P. 263 129, India

THE PROBLEM OF ANISOTROPY OF INERTIA

Z. Horák, Czech Technical University, Praha

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It is shown that the original formulation of Mach's principle, essentially equivalent to the general principle of relativity, does not suggest any arguments for the anisotropy of inertia in accordance with the fact that the principle of equivalence implies that an accelerating point mass, embedded in an otherwise homogeneous universe, exerts an additional inertial force, parallel to the acceleration of the point mass, which does not depend on the direction of the line connecting the particle with the point mass, on a test particle at rest.

К вопросу анизотропии инерции

В статье показано, что первоначальная формулировка принципа Маха, по существу совпадающая с общими принципами относительности, не приводит к аргументам к пользу анизотропии инерции. Из принципа эквивалентности следует, что ускоряющая точечная масса, добавленная в однородную Вселенную, вызовет на пробной частице дополнительную инерциальную силу, параллельную с ускорением, вызванным точечной массой и не зависящую от направления прямой соединяющей пробную частицу с точечной ускоряющей массой.

1. Introduction

Cocconi and Salpeter (1958) suggested that one of the possible consequences of Mach's principle was that the asymmetric position of the Galaxy with respect to the Earth induces an asymmetry in inertia. They proposed a test of this effect, consisting in the microwave measurement of the Zeeman splitting of electron levels having different orientations, relative to the direction Earth — centre of the Galaxy. The isotropy of inertia on the Earth could thus be checked with an accuracy of about 1 part in 10^{11} . In a subsequent paper Cocconi and Salpeter (1960) proposed the use of the Mössbauer effect in a search for the anisotropy of inertia and estimated that such experiments would put an upper limit of about 10^{-14} on the measure of the anisotropy.

The problem drew the attention of both theoretical and experimental physicists as will be shown in Section 3. Here, the author will confine himself to the statement that the most accurate measurements resulted in the much lower limit 10^{-22} , but that, however, the theoretical significance of this fact is not clear. Whilst

Epstein and Dicke regard it as a support for Mach's principle, Weber believes that it provides no support for a strong form of this principle.

This discrepancy in theoretical viewpoints is rather remarkable and mainly the latter statement due to Weber seems to be a very serious one. Thus the author will analyse it thoroughly in the present paper in order to see if it corresponds necessarily to the spirit of Mach's principle.

In Section 2, the authentic formulations of Mach's principle, given by himself in 1872, are quoted.

In Section 3, the idea of the anisotropy of inertia, or of the so-called "mass anisotropy" is outlined according to Cocconi, Salpeter, Hughes and Wheeler.

In Section 4, the experiments performed are indicated and their interpretations by Epstein, Dicke and Weber are given.

In Section 5, it is shown that the principle of equivalence leads to the result that an accelerating point mass exerts an elementary Machian force, parallel to the acceleration of the point mass and inversely proportional to its distance from the particle, on a test particle at rest. It is, however, independent of the