The OH radical in Comets : Observation and Interpretation of the 18 cm wavelength Radio Spectrum.

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Summary

We have completed a quantitative analysis of the 1667 Mhz observations of OH in comets Kohoutek (1973 XII) , Kobayashi-Berger-Milon (1975 IX) , West (1976 VI) , Kohler (1977 m) and Bradfield (1978 c) ; some preliminary results on comet Meier (1978 f) are presented.

In all comets the 1667 Mhz line closely follows the predictions of the U.V. pumping model of Biraud et al. (1974) and Mies (1974); all four hyperfine transitions at 1612 Mhz, 1665 Mhz , 1667 Mhz and 1720 Mhz were detected in comet Meier and found compatible with the L.T.E. ratios of 1 , 5 ,9 , 1.

Fitting Haser's model (1957) to the observations of comets Kohoutek , West and Kohler leads to pairs of values of the parameters L_{OH} , L_P respectively the scalelength of OH and its parent molecule : for $L_P = 1 \pm 0.25\ 10^5$ km , $L_{OH} = 6^{-1.5}_{+3}\ 10^5$ km at 1 a.u. heliocentric distance (r_H) and the corresponding OH lifetime is $4^{-1}_{+2}\ 10^5$ s.

There is indication that the OH maser is quenched by collisions in the inner coma and similar evidence is found from the comparison of high resolution U.V. spectra with synthetic spectra of the 3090 Å band.

The production rate of the parent molecule of OH (Q_P) is computed for all comets observed sofar at 1667 Mhz : for new comets in the range $0.8 < r_H < 2.6$ a.u. the variation of Q_P versus r_H often deviates from a r_H^{-2} law but there is good agreement between Q_P^o (Q_P reduced to 1 a.u. with a r_H^{-2} law) and I_o (the concomitant visual brightness reduced to 1 a.u. with a r_H^{-4} law). Similarly Q_P^o is proportional to I_o from comet to comet in the range $4\ 10^{27} < Q_P^o < 4\ 10^{29}$ mol. s^{-1}.

I. Introduction

With comets Kohoutek (1973 XII) and Bradfield (1974 III) the future of cometary radio spectroscopy appeared very promising by mid-1974 : a harvest of new as well as already known molecules had been made namely CH_3CN , HCN , H_2O , CH and OH . By mid-1979 the field is in complete stagnation except for the OH radical: many comets approached the Sun among which bright ones but there is no confirmation of microwave emissions of CH_3CN , HCN , H_2O or CH. On the contrary the 18 cm wavelength Λ doublet of OH was observed in comets Kobayashi-Berger-Milon (1975 IX) (Gerard et al.,1977), West (1976 VI) (Webber et al.,1976 a,b;Snyder et al.,1976 ; Bowers and A'Hearn,1976 a,b;Gerard et al.,1976,1977),d'Arrest (1976 XI) (Webber and Snyder,1977), Kohler (1977 m) (Despois et al.,1977), Bradfield (1978 c) (Despois et al.,1978) and more recently Meier (1978 f) (Crovisier et al.,1978). The case of comet Encke (1786 I) is not considered here since the detection claimed by Webber et al.,(1977) is not unambiguous (Bania,1977).

Our 18 cm OH radio observations were presented at the U.R.S.I. XIX General Assembly (Gerard, 1978) and are fully described and analysed (except comet Meier) in a forthcoming publication (Despois et al.,1979). The sample becomes sufficient to venture comparisons with U.V. spectroscopy and photometry of the 3090 Å band on the one hand (which started long ago in comets (Swings et al.,1941)) and with observations in white light on the other hand (which although less specific provide an almost continuous monitoring of the overall activity of the nucleus).
This is the twofold purpose of this paper in which we discuss successively the excitation of the OH radical , its lifetime and finally the production rate of its parent molecule (presumably H_2O)

II. The excitation of the OH molecule :

1°. The 4 hyperfine components at 1612,1665,1667 and 1720 MHz.

It was recognized long ago (Hunaerts,1953 ; Swings and Haser,1956) that fluorescent pumping of the OH molecule by U.V. solar radiation (the so-called Swings effect) satisfactorily accounts for the intensity distribution within the $A^2\Sigma^+ - X^2\Pi v(0-0)$ band at 3090 Å and its extreme dependence on heliocentric radial velocity (v_H) . A detailed comparison between high resolution spectra and synthetic spectra was not possible however because the rotational transition probabilities were unknown and the solar Fraunhofer spectrum of insufficient quality. Thus the best spectrum of the OH band , that of comet Burnham (1960 II) on May 2,1960 (Dossin et al.,1960) still remains to be interpreted.
The Swings effect could be expected to exert a strong influence on the 18cm transition between the upper and lower parity states of the $^2\Pi_{3/2}$,J=3/2 ground

state where most of the OH molecules reside as was indeed found (Biraud et al.,1974; Mies,1974 ; Turner,1974). Due to the proton nuclear spin the 18 cm transition splits into 4 hyperfine components namely F(2-2) at 1667 MHz,F(1-1) at 1665 MHz , F(1-2) at 1612 MHz and F(2-1) at 1720 MHz and the ground state consists of 16 magnetic M_F sublevels. Now Mies(1976) has shown that for $v_H = \pm 41$ km/s (and we have extended the calculations to the whole range $-55 < v_H < +55$ km/s) the unidirectional pumping by the Sun will only produce small deviations of the hyperfine population distributions from an equilibrium population provided the following conditions are met :

a) the U.V. absorption rate is fast compared to any other processes like collisions or I.R. pumping that may alter the ground state population.

b) the coma is optically thin at all transition wavelengths.

c) the OH gas is not exposed to any magnetic or electric fields .

Then little polarization should ensue and the 1667 , 1665 , 1612 and 1720 MHz line intensities be close to the L.T.E. values of 9 , 5 , 1 , 1.

The observations show (Gerard et al.,1977 ;Webber and Snyder,1977,Despois et al., 1979) that the 1667 MHZ line closely follows the U.V. pumping model in all comets and throughout the heliocentric radial velocity range -50 to +50 km/s (see Fig.1). However in comets West and d'Arrest Webber and Snyder find that the 1665 MHz line is more inverted than the 1667 MHz line ; prior to comet Meier our data do not permit a good determination of the 1667/1665 line ratio but in this last comet we were able to detect for the first time the two satellite lines at 1612 and 1720 MHz and to measure the 1667/1665 line ratio (see Fig.2). Between 13 July and 13 August 1979 all 4 lines are compatible with the L.T.E. ratios and in agreement with the 1667/1665 line ratio obtained by Bania(1978)with the Arecibo Radiotelescope.

On 3 days only spread over the period 21 June-15 August the 1665 MHz line appears much fainter while the 1667 MHz intensity is comparable to other days; thus the 1665 MHz line was less inverted sometimes than the 1667 MHz line contrary to what Webber and Snyder found in comets West and d'Arrest. Clearly the matter is far from settled but again there is no indication of an anomalous behaviour of the 1667 MHz line.

2°. The quenching of the OH maser by collisions in the inner coma.

An indication for the quenching of the ground state population inversion in the inner coma came rather unexpectedly when we tried to fit Haser's model(1957) to the 1667 MHz data of comets Kohoutek , West and Kohler : these comets were observed simultaneously by the Nançay and at least another radiotelescope of different beam size and/or by the Nançay radiotelescope at offset positions from the nucleus. With typical values of $1 \pm 0.25\ 10^5$ km for the scalelength of the parent molecule (L_P) one finds $L_{OH} = 7.5^{-1.5}_{+1.5}\ 10^5$ km at $r_H = 1$ a.u. The model fitting gives better agreement however if one assumes that the population inversion is quenched by collisions in the inner coma: a quenching up to 4 10^4 km distance from the nucleus lowers L_{OH} to $6^{-1.5}_{+3}$ 10^5 km for the same. L_P values . The first condition for inverting the population of the Λ doublet is no longer fulfilled when the collision rate overruns the U.V. absorption rate ($\sim 10^{-3}$ s^{-1} at r_H =1 a.u.) : once the double is thermalized the spontaneous emission is negligible (Biraud et al.,1974) and the "radio observations" do not "see" the OH molecules near the coma centre. The reasons for invoking collisions are many:

a) Malaise (1970) has shown that the collisional excitation rate of the rotational levels of CN is 10^{-2} to 10^{-3} s^{-1} at 1 . 10^4 km from the nucleus.

b) Bouloy and Omont (1977,1979) have studied in great detail the transitions across Λ doublets of OH induced by collisions with ions, electrons and neutrals. The ion rates in particular are very high ($K \simeq 10^{-5}$ $cm^3.s^{-1}$) due to the dipole monopole interaction and the small energy required for the Λ doublet transition compared to rotational transitions. Thus ion densities of the order of 10^2 cm^{-3} will suffice to quench the inversion and such densities are currently found well above 1 10^4 km from the nucleus in the ionospheric models of Shimizu (1976) and Ip and Mendis (1976,1977).

c) there is evidence for the quenching in the high resolution spectra of the 3090 Å band : their fitting with synthetic spectra calculated with the U.V. pumping model is much better when one assumes that a significant fraction of the OH molecules are thermalized. For comets Cunningham (1940 c) (Swings and Haser,1956) Burnham (1960 II) (Dossin et al.,1961) and Kohoutek (1973 XII) (Lane et al.,1974) the fraction varies between 30 and 100 percent. The case of comet Burnham is illustrated on Fig.3.

III. Scalelength , velocity and lifetime of the OH molecule.

When the OH expansion velocity is a delta function $\delta(v-v_0)$ as assumed in Haser's model the line profile should be a square function for an infinite beam (stricto sensu this is only true when there is no Greenstein effect). In comets West and Kohler we find v_0 = 1.5 km/s. at r_H =1 a.u. , then the OH lifetime (τ_{OH}) is 4^{+2}_{-1} 10^5 s. This value is in good agreement with the theoretical estimates (see e.g. Wallis,1973) ; it should be emphasized that the radio measurements have provided the first direct measurement of the expansion velocity since the U.V. spectral resolution of the 3090 Å band is too low and that no indirect determination was attempted using the Greenstein effect as Malaise (1970) did for the CN radical. In any case the long standing discrepancy remains between the radio scalelength (L_{OH} = 6 10^5 km)and the optical scalelength (L_{OH} = 2 10^5 km; Keller and Lillie, 1974; Blamont and Festou, 1974). Festou (1978) has recently shown however that when the daughter molecule is produced by photodissociation of a parent molecule with an excess velocity, that velocity must be added vectorially to the expansion velocity of the parent: for the OH radical the residual velocity is ~ 1.2 km/s. if the parent is H_2O then some molecules can travel backward towards the nucleus while others move forward at increased speed. The net result is that the apparent mean radial velocity should increase with cometocentric distance. From the isophotes of comet Kohoutek (Blamont and Festou, 1974) Festou finds a revised lifetime of $2^{+2}_{-0.7}\ 10^5$ s. not incompatible with the radio lifetime of $4^{+2}_{-1}\ 10^5$ s. The above considerations strongly plead for accurate Doppler velocity measurements of the OH radical in cometary heads; a first step was accomplished in this direction with comet Meier that we observed on August 14, 1978 with a velocity resolution of 50 m/s. The 1667 MHz profile is shown on Fig.4.

IV. The OH parent production rate : variation with heliocentric distance and correlation with total visual magnitude.

By applying Haser's model in a self consistent way i.e. with the parameters hitherto derived from radio data alone we have computed the OH parent production rate (Q_P) of all comets observed sofar at 1667 MHz (there is no direct proof that H_2O is the parent molecule of OH and we have preferred the wording OH parent production rate rather than OH production rate). The determinations of Q_P by means of radio and optical techniques being completely independent it is useful to compare them when simultaneous (or nearly) measurements are available: thus comet Kohoutek was observed at 3090 Å on 15 Jan.1974 ($r_H = 0.62$ a.u.) by Blamont et al., 1974 and on 24 Jan. ($r_H = 0.88$ a.u.) by Harvey et al., 1974) and also at 18 cm on 19 Jan. ($r_H = 0.75$ a.u.) by Biraud et al., 1974. The Q_P values reduced to 1 a.u. assuming a r_H^{-2} dependence are respectively 3.2, 1.6 and 3 10^{28} mol.s^{-1} a rather good agreement since both U.V. observations were made onboard aircrafts where the absorption by atmospheric ozone is a major source of error.

We have sofar detected the OH radical at 1667 MHz in comets between $r_H = 0.4$ (Kohoutek) and 2.6 a.u. (Meier) and it is clear that the commonly used r_H^{-2} law for Q_P is only a crude approximation valid within a factor of 2 or 3. (see Fig.5) On the other hand there is a remarkable agreement between Q_P° (Q_P reduced to 1 a.u. with the r_H^{-2} law) and the total visual brightness itself reduced to 1 a.u., I_o*, (assuming a r_H^{-4} variation)

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* The "absolute luminosity" is taken from Comet News Service (Issue n°78-7) edited by J.Marcus.

While the comet remained invisible for almost 4 moths the 18 cm OH radio observations provided a useful monitoring of the overall activity and witnessed the drastic decline of gas production between July and November 1978.

That the OH parent production rate agrees well with the visual brightness performance of the cometary coma was already noted by Keller and Lillie (1978) for comet Tago-Sato-Kosaka (1969 IX) which did not decrease according to an exponential law between r_H =1.03 and 0.78 a.u. The statistics are too sparse or inaccurate at the present time to decide what is systematic in the variation of Q_P versus r_H ; part of it is certainly genuine activity and Keller and Lillie (1974) found a completely different behaviour of Q_P in comet Bennett near 1 a.u.

The excellent correlation between Q_P^o and I_o for different comets is illustrated on Fig.6 : the OH parent production rate is clearly proportional to the total visual brightness in the case of new comets over a range of two orders of magnitude. Since the visual brightness is due both to continuous radiation scattered by the dust and to emission lines of C_2 , CN , CO^+ ... a different behaviour could be expected from comets with different dust/gas ratios , using e.g. Donn's (1977) qualitative classification in High , Medium and Low dust/gas ratio : although the sample is small there is no clear trend on Fig.6. The total visual brightness is so difficult to interpret however that the significance of the relation $Q_P^o - I_o$ cannot be assessed at the present time but it is useful already to predict the intensity of the 18 cm signal when a new comet is discovered like comet Meier in late May 1978 (Crovisier et al.,1978).

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Legend of Figures

Fig. 1 : inversion of the ground state population of OH versus heliocentric radial velocity (full line). The velocity range where the U.V. pumping model was tested is indicated by the shaded area.

Fig. 2 : the 4 hyperfine components at 1612 MHz , 1665 MHz , 1667 MHz and 1720 MHz in comet Meier (1978 f) between 13 July and 13 August 1978.

Fig. 3 : comparison between the high resolution spectrum of the 3090 Å band in comet Burnham(1960 II)(Dossin et al.,1961)(full line) and synthetic spectra with an increasing fraction of the OH molecules thermalized by collisions :

(a) no quenching

(b) 50 percent quenching

(c) 100 percent quenching.

Fig. 4 : high resolution profile of the 1667 MHz transition in comet Meier (1978 f):

(a) usual resolution of 1 km/s on 15 August.

(b) high resolution of 50 m/s on 14 August.

(c) same as (b) on an empty field taken on 14 August.

Fig. 5 : long term variation of the OH parent production rate and visual brightness of comet Meier (1978 f).

Fig. 6 : the correlation between OH parent production rate and visual brightness in comets. The symbols are :

-d'A : d'Arrest (1976 XI)

-E : Encke (1786 I)(upper limit)

-B : Bradfield (1978 c)

-KBM : Kobayashi-Berger-Milon (1975 IX)

-KO : Kohler (1977 m)

-K1 : Kohoutek (1973 XII) preperihelion.

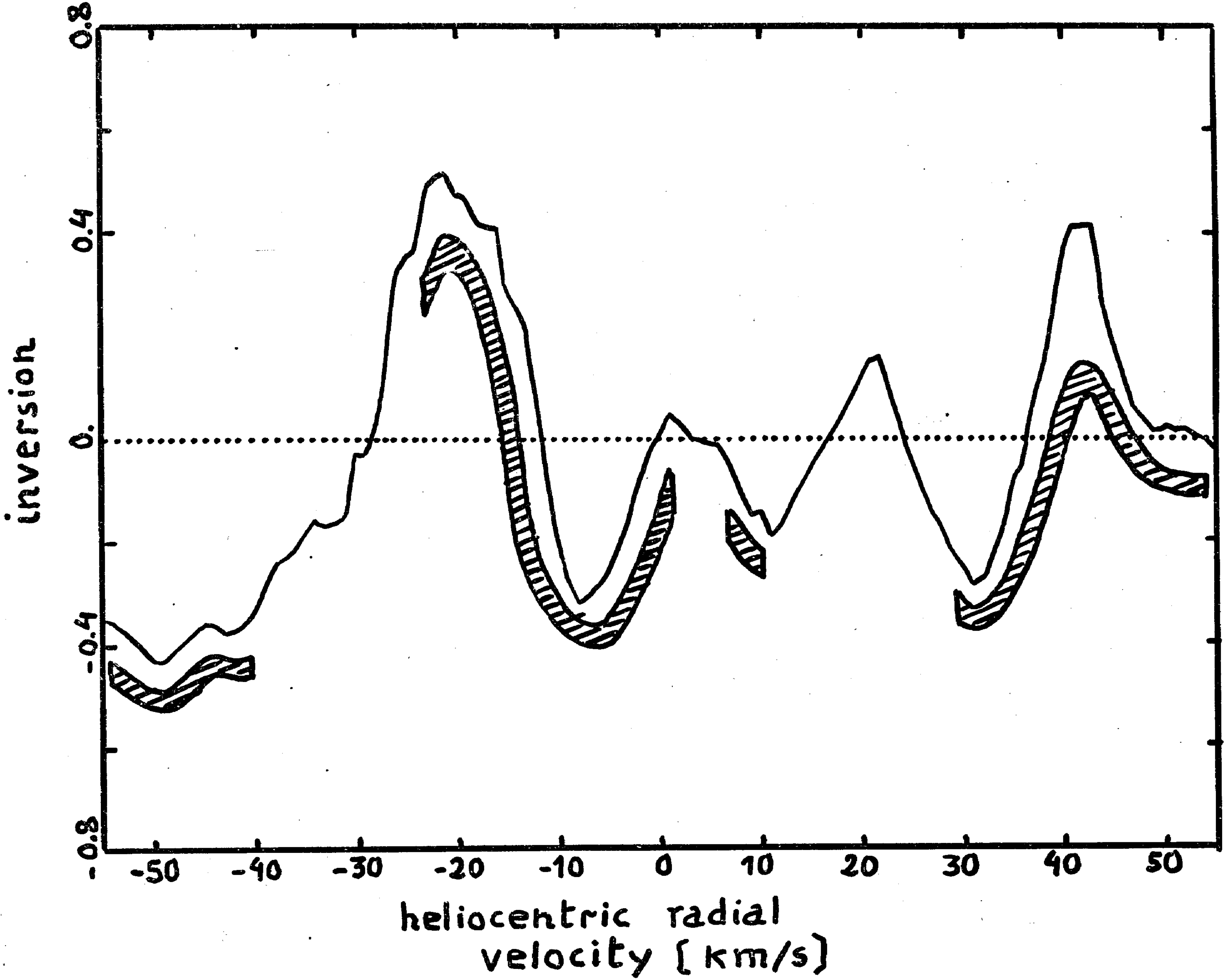
-K2 : same postperihelion.

-W : West (1976 VI)

-M : Meier (1978 f)

: the letter in brackets indicates the dust/gas ratio : either High , Medium or Low.

Fig.1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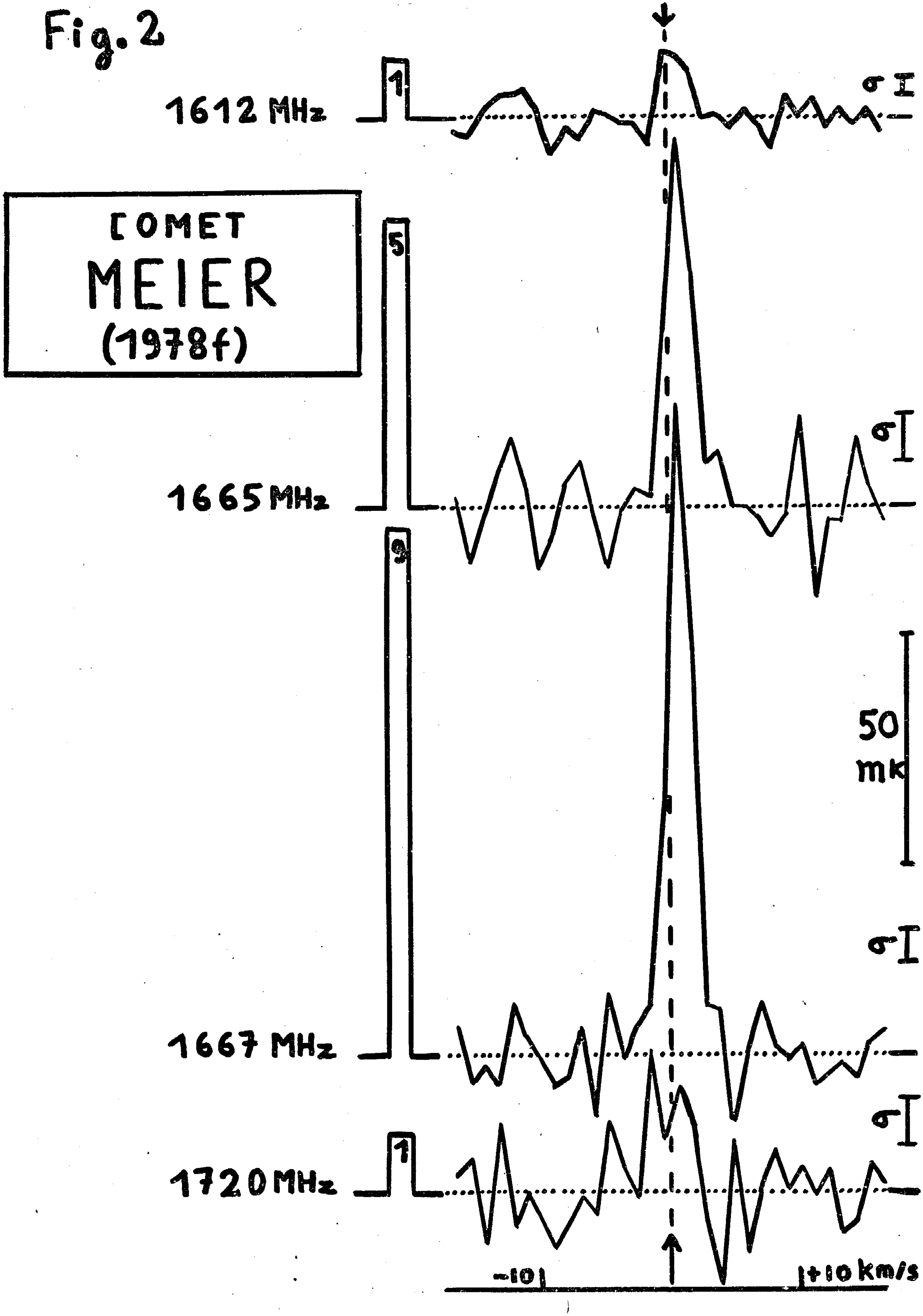
0.4
0.
-0.4
-0.8
-50
-40
-30
-20
-10
0
10
20
30
40
50
heliocentric radial velocity [km/s]

Fig. 2


COMET
MEIER
(1978f)
1612 MHz
1
σ
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5
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1667 MHz
9
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σ
-10
+10 km/s

Fig. 3

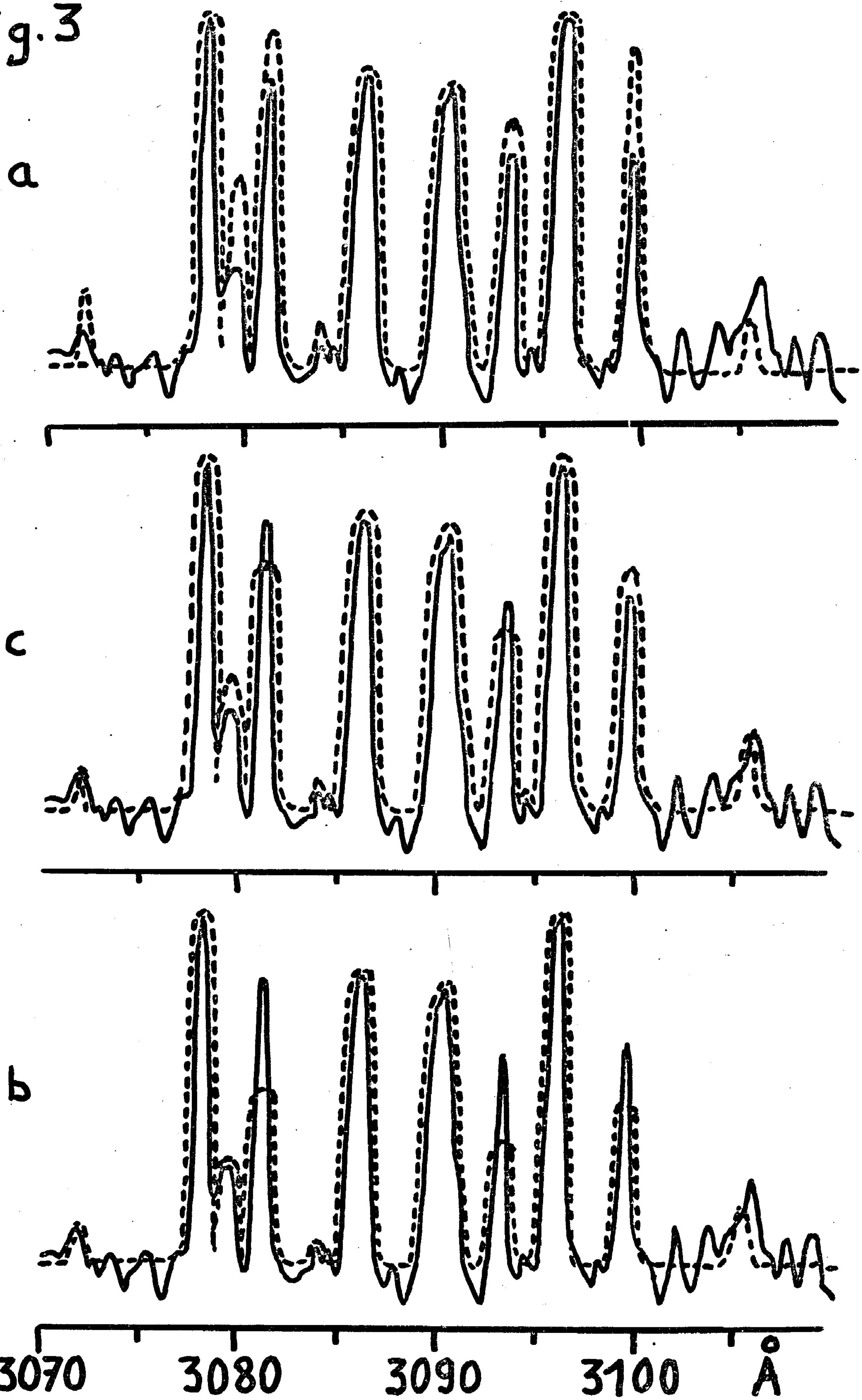


Fig. 4

$^2\Pi_{3/2}$, $J=3/2$ $F=2-2$

HYPERFINE TRANSITION OF OH at 1667.35903 MHz (REST FREQUENCY)

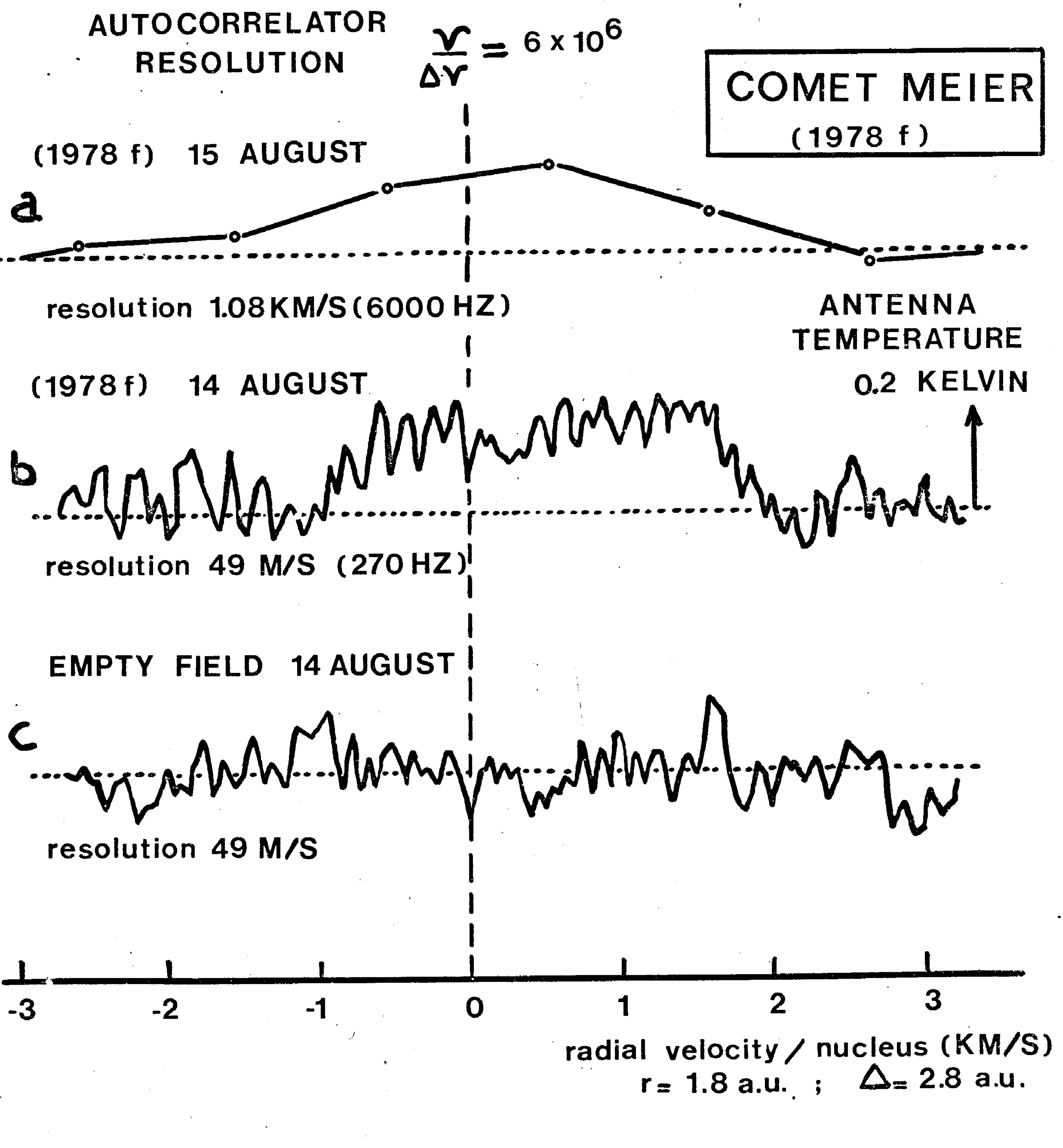
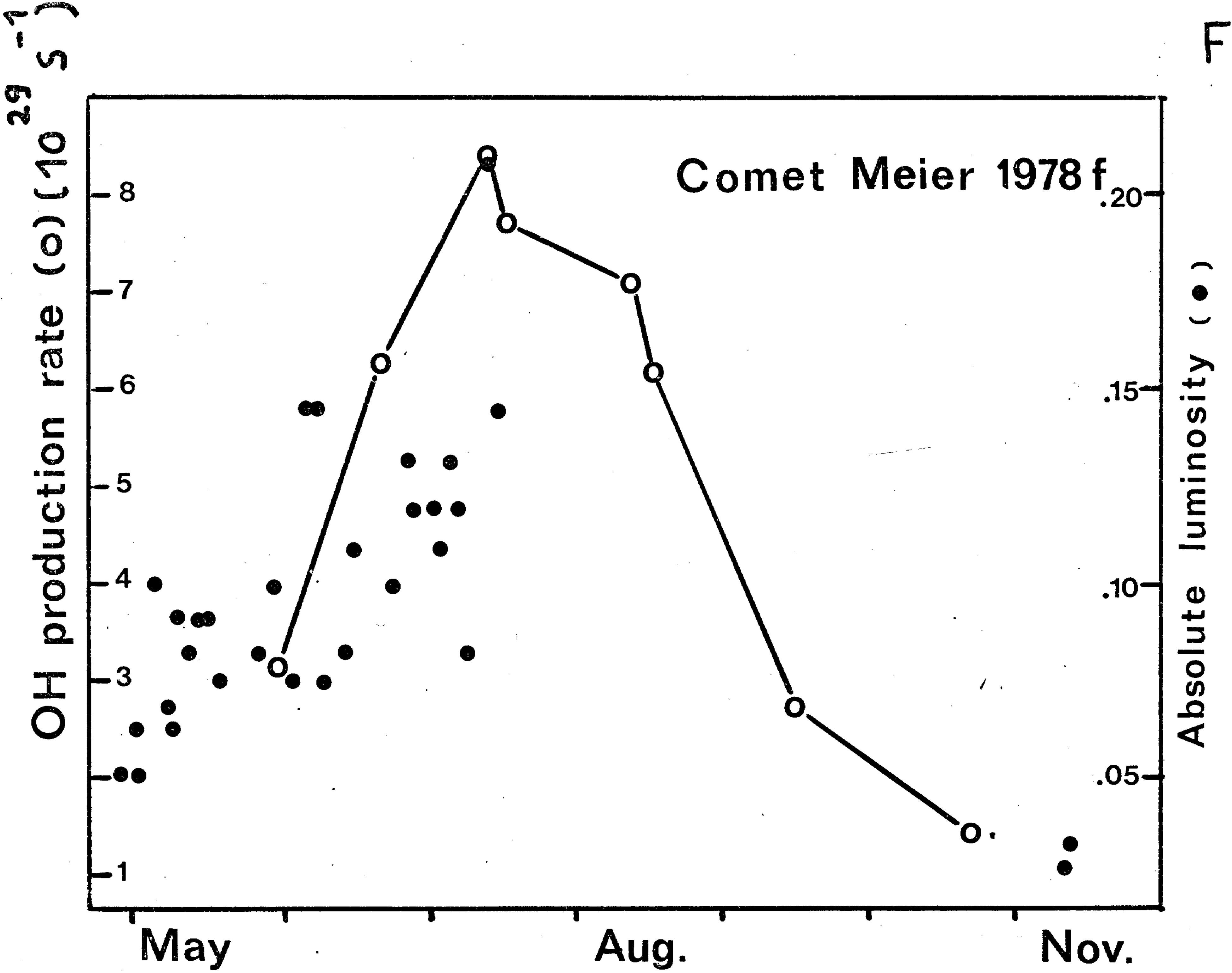


Fig.5


Comet Meier 1978 f
OH production rate (o) (10^29 s^-1)
Absolute luminosity (●)
8
7
6
5
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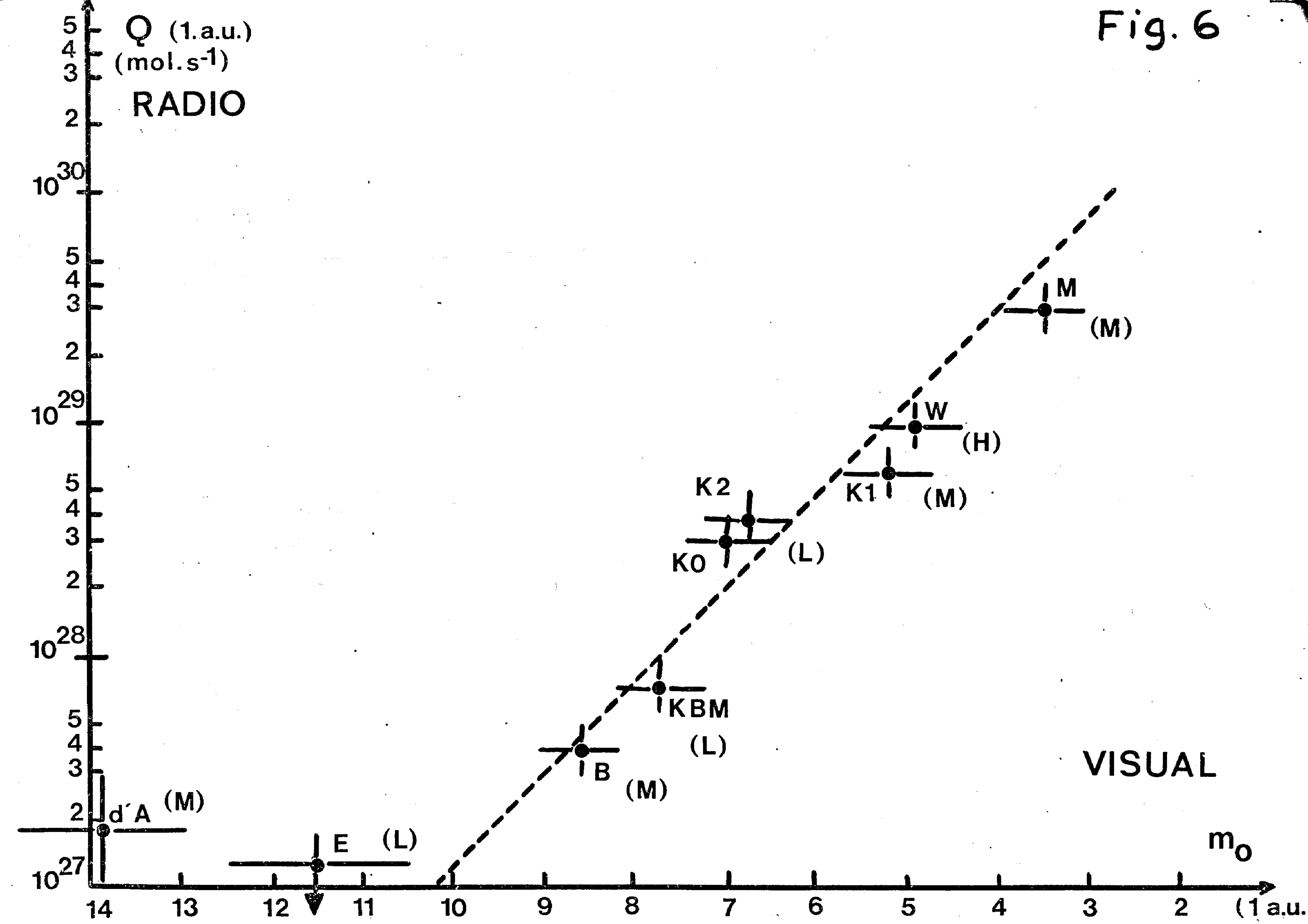
3
1
.20
.15
.10
.05
May
Aug.
Nov.

Fig. 6


Q (1.a.u.)
(mol.s-1)
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m_o
(1 a.u.
M
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