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COMET P/HALLEY: VISUAL MAGNITUDE ESTIMATES AND GAS PRODUCTION

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ABSTRACT

More visual magnitude estimates have been made of comet P/Halley than of any other comet in history. This unique data base allows to work out systematic sources of error and to remove them by a rigid selection procedure. From the remaining sample brightness laws of two different types are deduced.

In a second step, several studies of molecular production rates and their changes during the 1985-1986 apparition of P/Halley are compared with these laws in order to obtain formulae transforming visual magnitude estimates directly into production rates, esp. for Hydroxyl (OH). Inconsistencies between different studies could not be reconciled, so only vague conclusions are possible. The dust content of a comet is cited as a potentially complicating factor in obtaining a simple law. An outlook for other comets is given.

Keywords: visual magnitude estimates, gas production rates, contribution of dust, power laws in comets

1. THE VISUAL MAGNITUDE ESTIMATES: CRITERIA OF DATA SELECTION

1.1 Introduction

Until recently, visual estimates of cometary magnitudes were the only means to determine the most prominent parameter of a cometary coma: its total brightness, i.e. the brightness the comet would have being reduced to a point source. The vast majority of data regarding the brightness behaviour of comets consists of visual comparisions with stellar magnitudes. Even today, the visual magnitude estimate (v.m.e.) remains the only method to determine the total light of even a moderately extended coma.

Mainly in order to obtain a set of observations that can be compared with those of the last apparition, observers had been encouraged to provide v.m.e.'s during P/Halley's 1985-1987 apparition (Ref. 1). The result is an unprecedented wealth of data that may total 10^4 independent data points worldwide, published e.g. in the International Comet Quarterly, The Astronomer and the bulletins of numerous national networks.

1.2 Systematic observational errors

In recent years consistent methods for obtaining v.m.e.'s have been developed (Ref. 2) and were followed by most contributors to the different networks. Nonetheless there is a tremendous scatter of the results reported by different observers at the same time. As experienced with many other comets before, e.g. 1984e Giacobini-Zinner (Ref. 3), the published visual magnitudes differ by more than 2 mag or a factor of 6 in intensity.

Three major sources of systematic errors can be found (besides the use of inadequate comparision stars and other elementary errors):

> the brightness of the background sky,
> the use of different instruments and
> different subjective opinions on when a defocused star's image matches a comet's head.

Especially the last point often introduces irreproducible personal effects (Ref. 4). Some subtle effects were also elaborated recently by IHW's S. Edberg et al. (Ref. 5).

Typically, for an analysis an arbitrary group of 'experienced' observers is selected (e.g. in Ref. 6) while all other data are completely ignored. In contrast, this study will first evaluate the complete multitude of observations before a decision on a useful selection is made. All brightness laws will be based upon this sample.

1.3 Data selection and reduction procedures

Only for the reduction of instrumental effects a formalism has been developed so far, and even its application - the standard 'aperture correction'- is not guaranteed to work (Ref. 7,8). The existence of an aperture effect was prominent to many observers of Halley's comet (the selection method of Ref. 6 made it seem to disappear). Doubts have been voiced whether the telescope's aperture, magnification or even its exit pupil is the crucial parameter (Marcus, Kirsch, private communication). It is well possible that better correction parameters can be found from the truly redundant Halley data. One must not forget that Morris (Ref. 7) had strongly urged to test his findings at every comet anew! For this study a modified version of Morris' initial formulae (with less correction for very large telescopes) has been applied.

In principle it should be possible to eliminate the (sometimes strongly) contrast-lowering influence of the background sky, too, as it can be measured by noting the faintest star visible to the naked eye in the field of the comet. Though most observers' networks ask for this information they usually do not provide it in their listings (Ref. 9). With

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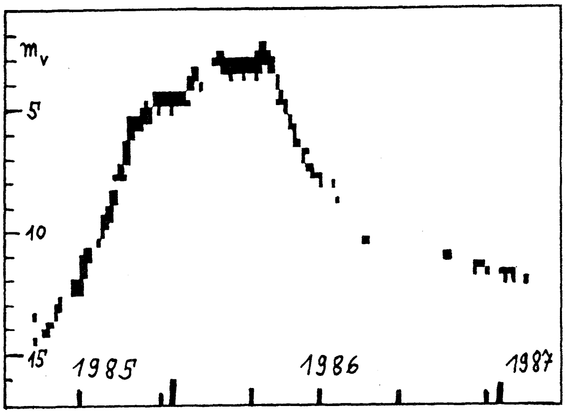

Figure 1. Halley's light curve derived from 386 visual magnitude estimates (the selection on which all calculations in this paper are based). Shown is the apparent magnitude but with aperture correction.

these data available there will be attempts to deduce some empirical 'dimming' effect on the comet estimate's outcome.

The personal effects are the worst problem and cannot be handled at all yet. Controlled experiments in preparation here might allow one day to arrive at 'personal equations' for selected observers, but we will never have them for all international contributors. Therefore a somewhat arbitrarily-looking procedure will be applied now in order to get a 'cleaned' subset of observations for further mathematical treatment.

Based upon the experience that all non-instrumental influences make a comet appear fainter, the brightest estimates in a given interval of 12 to 24 hours were strongly favored. As expected the final light curve resembles those based on selected observers, and it is difficult to judge which one represents the real trend more accurately. Again: the rejection of several thousands of observations under both selection principles does not mean that they are plainly wrong. It is necessitated by our inability to adjust them for factors beyond the observers' control.

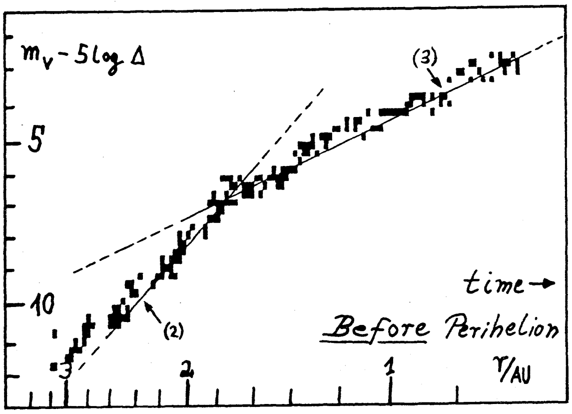

Figure 2. Heliocentric magnitude versus logarithm of heliocentric distance before perihelion. For comparision with predictions see Refs. 12, 3. Fits (2) and (3) are indicated.

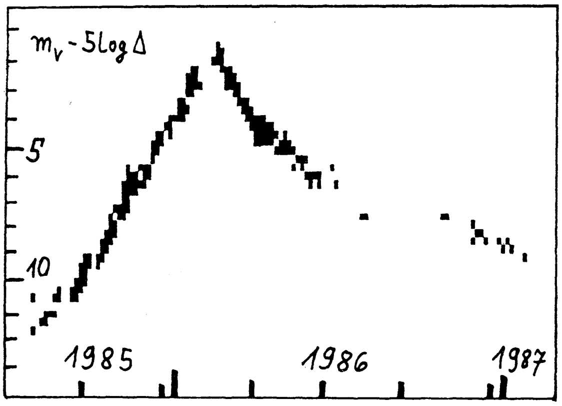

Figure 4. The same light curve as in Fig. 1, but showing the 'heliocentric magnitude' as a function of time. This is the apparent magnitude an observer travelling 1 AU from the comet would see.

2. DESCRIPTION OF P/HALLEY'S BRIGHTNESS

2.1 Observations from August 1985 to perihelion

Fig. 1 shows Halley's geocentric brightness as a function of time. Two maxima of about 2.5 mag (reduced to 6.78 cm standard aperture; being equal to about 2.0 mag for the naked eye) are seen in late February and early April 1986. For the anticlimactic part of the apparition not all networks could be evaluated for this study, so the scarce data for June 1986 to January 1987 should be taken as preliminary.

In most cases a comet's brightness is described best as a function of the heliocentric distance, by the so called 'standard power law formula' which also makes most 'sense' in terms of physical mechanisms (Ref. 10):

$$m_1 = m_0 + 2.5\, n \log r + 5 \log \Delta \qquad (1)$$

with m_1 the total magnitude, m_0 the comet's magnitude at 1 AU heliocentric distance, r and Δ the heliocentric and geocentric distances of the comet in AU and n a crucial parameter describing how much brighter the comet becomes with decreasing r. A search for the proposed Delta-effect (Ref. 11)

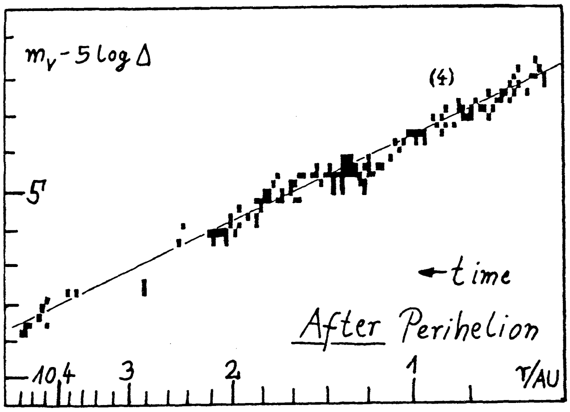

Figure 3. Heliocentric magnitude versus logarithm of heliocentric distance after perihelion. A large gap in the data is caused by a bad viewing geometry, but fit (4) easily incorporates all data.

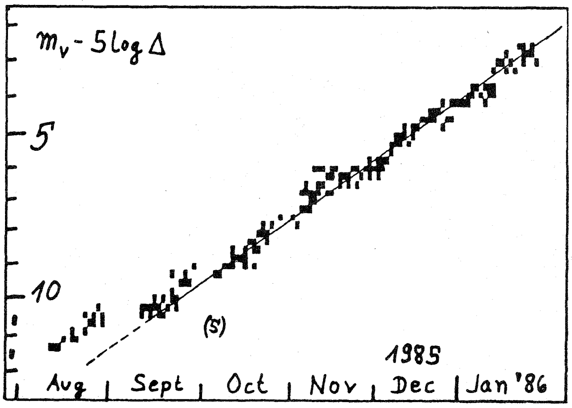

Figure 5. Detail of Fig. 4. Heliocentric magnitude versus time. Five months of data can be fitted by one law, formula 5. Preperihelion data.

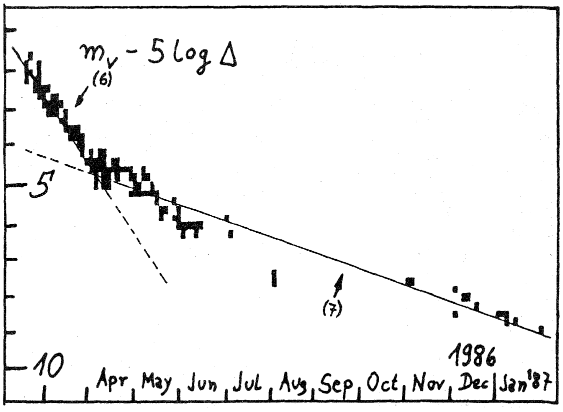

Figure 6. Detail of Fig. 4. For the postperihelion data, a fit by one law obviously is impossible. Two trials, formulae 6 and 7 are shown.

was beyond the scope of this study but should be worthwhile.

From careful analyses of P/Halley's last apparition several predictions for m_0 and n before and after perihelion were published (e.g. Refs. 13,14, 15,11, reviewed in 16). Morris and Green (Ref. 14) expected an (m_0,n)-tupel of (5.47,4.44) before and (4.94,3.07) after perihelion. Bortle and Morris (Ref. 15) supported the preperihelion predictions but changed the postperihelion tupel to (3.1,3.1). While giving considerably brighter parameters Marcus (Ref. 16) came to the same basic conclusion: one formula should describe the whole apparition before and one other formula the whole apparition after perihelion, at least when the comet was active at r < 3.5 AU.

The observed behaviour, however, was markedly different. Before perihelion (Fig. 2) clearly two standard power law formulae are needed to fit the data properly. For at about r = 1.7 AU Halley's comet had abruptly changed its 'reactivity' to the increasing sunlight: the parameter n decreased suddenly from about 8.5 to about 3.8. The two formulae derived from Fig. 2 are:

$$m_{\mathrm{pre},\ r>1.7\ \mathrm{AU}} = (1.6\pm0.5) + 2.5(8.5\pm0.5)\log r + 5\log\Delta \quad (2)$$

$$m_{\mathrm{pre},\ r\leq1.7\ \mathrm{AU}} = (4.2\pm0.2) + 2.5(3.8\pm0.3)\log r + 5\log\Delta \quad (3)$$

2.2 Observations after perihelion till January 1987

After perihelion the fade of Halley's brightness (its maximum was reached between one and two weeks after perihelion) took place in a much simpler way. Although parts of the light curve so far available are rather incomplete, mostly due to a bad viewing geometry in summer 1986, it doesn't seem that there was another change of slope. Indeed: for the first time during this apparition the predictions based on the months February to July 1986 held true when Halley's was recovered in late October. The formula

$$m_{\mathrm{post}} = (3.85\pm0.15) + 2.5(2.75\pm0.15)\log r + 5\log\Delta \quad (4)$$

nicely fits the remaining six months of the 'hot' apparition as well as the third visual observing season extending well into 1987.

2.3 Comparing the 1909/11 and 1985/87 apparitions

The similar value of m_0 in Eqs. 3 and 4 puts the intrinsic brightness of P/Halley at approx. 4^{m}0 which is 1 to 1.5 mag brighter than calculations based on the last apparition had yielded. It is not very likely that a comet brightens through ageing, and indeed this discrepancy is almost certainly due to a considerable progress in observational techniques since 1910. Morris (Ref. 17) succeeded in reproducing the 'old' methods during the current apparition: by ignoring the growing coma diameter during the November 1985 perigee and still using a large reflector with high magnification instead of the advisable binoculars he noted a brightness development similar to the one reported 75 years earlier. 'His' n was only 5.5 as 'his' Halley never got brighter than 7 mag.

This simply means that this n=5 result probably was 'wrong' 75 years ago as well as it is wrong for us today. As we are interested in the total coma brightness, rating these observations as bad seems justified. Thus we can conclude that the apparitions of 1910 and 1985 were rather similar in respect of total magnitude - a confirmation of Marcus' radical thoughts regarding the 1910 apparition (Ref. 16) ! His failure to know of the change of slope in advance is simply due to a lack of data points at the crucial months in early 1910. Anyhow, this means that we always have to use two formulae before perihelion for this comet - unless we try another form of equation.

2.4 An alternative way to describe the light curve

The idea is to replace log(r) by time as abscissa. No obvious physical mechanism has been invoked to justify this approach which distresses researchers (A'Hearn, private communication), but it works: Bortle who had applied this before to comet D'Arrest in 1976 (Ref. 10) noted a strikingly linear relationship between Halley's preperihelion brightness and time in his own observations (Ref. 18). In the data sample discussed here, there are two such laws, one valid for about 150 days before perihelion, the other for 50 days after perihelion (Figs. 5,6). They are

$$m_{\mathrm{pre}} = (2.0\pm0.3) + (0.057\pm0.003)T + 5\log\Delta \quad (5)$$

$$m_{\mathrm{post\#1}} = (1.5\pm0.5) + (0.057\pm0.007)T + 5\log\Delta \quad (6)$$

with T = the number of days before resp. after perihelion. Note the similar coefficients of T ! But in early April 1986 the slope of the time-dependent law dropped to about a fourth of the previous value. Unfortunately the now faint comet could not be observed under good conditions for months, so this formula is rather uncertain. It also cannot be excluded that subtle effects during the continuing fade of nuclear activity were missed. Ignoring weeks of large scatter in July and August 1986 (all observations were severely affected by a bad viewing geometry) the time-law seems to have changed to

$$m_{post\#2} = (4.0\pm0.5) + (0.014\pm0.005)T + 5\log\Delta \quad (7)$$

So, finally, we have the choice: two standard formulae before and one after perihelion or one time-formula before and at least two time-formulae after perihelion. This applies to the period of visibility in modest telescopes (August 1985 to February 1987); for an inclusion of earlier CCD photometry see Ref. 6.

The standard power law, though in essence not a physical but an empirical approach, is more likely to express fundamental processes governing the coma (Ref. 10). We should use Eqs. (2),(3) and (4) in order to understand how this light curve came into being.

3. VISUAL BRIGHTNESS AND PRODUCTION RATES

3.1 Complications

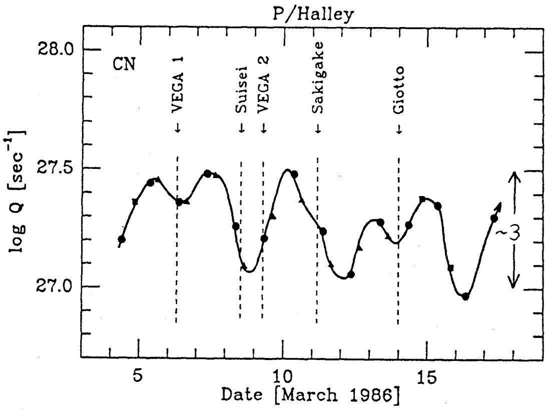

Figure 7. The production rate of CN in early March 1986; data from three observatories plus flyby times of the five Halley spacecraft. From Ref. 19.

As a comet's total brightness is controlled by the production of gas and dust, the question to ask now is: which relationship exists between the total visual magnitude and the production of different species ? Unfortunately this relationship is not direct: only the changes of the production rate at a timescale of weeks are reflected in the total magnitudes; the fluctuations (Ref. 19,20) over days (Ref. 21) or even hours (Ref. 22) have no counterpart in the total visual magnitude light curve. They are only coupled to changes of the 'central condensation', the inner arc seconds of the coma. A complete study of these near nucleus effects which were visible even in small telescopes must still be awaited, but it seems to be in preparation (Edberg, private communication).

Thus, it is necessary to determine the general trends in production rate developments. The fluctuations on shorter timescales which can cover factors of > 3 (Fig. 7) could lead to erroneous conclusions when the number of data points is too small - even if no systematic errors were existing (they are...) ! The following preliminary analysis will therefore discuss only those sequences of observations which cover large ranges of heliocentric distances r and consist of a sufficiently large number of observations. For the same reason all isolated determinations of production rates - how good they may be - had to be excluded.

It is beyond the scope of this study to discuss all the difficulties inherent in the procedures for deriving production rates from observed quantities. Though most published results were consistent with the in situ measurements by the spacecraft, we must not forget that this control is available only during one week in March 1986 and that the exponents of the different power laws could well be biased by unknown systematic effects. At least some must be as even different formulae for the same molecule obtained with different methods use to contradict each other.

Only a continuous record of measurements of prod. rates in situ by a spacecraft like CRAF (Neugebauer, this conference) will enable us to detect and remove these effects ! Thus the derived molecular production rates for P/Halley should be revisited when the CRAF results are in.

3.2 Results for OH and H_2O (derived from OH)

Naturally most studies on molecular production addressed the most important parent molecule and its most significant daughter.

3.2.1 Observations by the IUE satellite and Astron

Under the assumption that H_2O is the only parent of OH Feldman et al. (Ref. 23) have derived production rates from the UV surface brightness (Fig. 8).

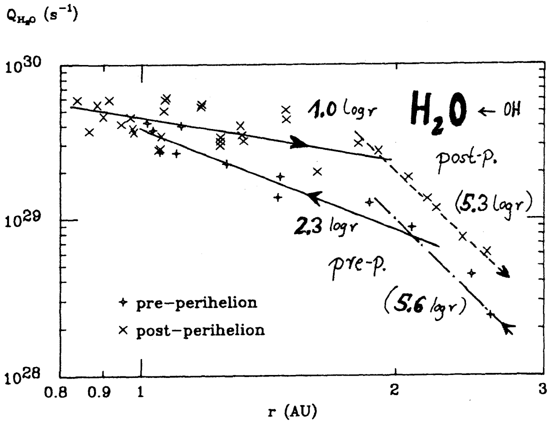

Figure 8. Water production of P/Halley derived from IUE observations of OH. From Ref. 23.

There seem to be changes of slope pre- as well as postperihelion at about 2 AU, but as the significance of the data at r > 2 AU is not clear, only the production rates Q at r < 2 AU will be discussed

$$\log Q_{OH,pre} = 29.6 - 2.3\log r \quad (8)$$

$$\log Q_{OH,post} = 29.6 - 1.0\log r \quad (9)$$

Q stands for the production of OH resp. H_2O in mol./sec., m for $m_1 - 5\log\Delta$ = heliocentric visual magnitude. Combining formulae (3) & (8) and (4) & (9) gives

$$\log Q_{OH,pre} = 30.6 - \underline{0.24}\, m \quad (10)$$

$$\log Q_{OH,post} = 30.2 - \underline{0.14}\, m \quad (11)$$

The smaller coefficient of m in Eq. 11, implying 'less magnitude for the same production' compared to Eq. 10 should be kept in mind.

The other UV observatory in orbit, Astron, also made observations of P/Halley (Ref. 24) - unfortunately too few to be comparable with the IUE results.

3.2.2 Radio observations with the Nançay radio telescope. The nearly daily monitoring of the 1667 and 1665 MHz transitions of the OH radical by Gérard et al. (Ref. 25) covered a full year: from July 1985 to July 1986. While there are periods of large scatter (Fig. 9), the two formulae

$$\log Q_{OH,pre} = 29.0 - 2.3 \log r \tag{12}$$

$$\log Q_{OH,post} = 29.2 - 1.2 \log r \tag{13}$$

describe the general trend quite well. Combining them with the brightness laws (3) and (4) yields

$$\log Q_{OH,pre} = 30.0 - \underline{0.24}\ m \tag{14}$$

$$\log Q_{OH,post} = 29.9 - \underline{0.17}\ m \tag{15}$$

The agreement with the IUE results (11) and (12) is very good - but it is very bad for r > 2 AU: here the IUE saw much more drastic in- and decreases of OH production. The reason for this discrepancy is not known. It may be noted that none of these studies resembles the visual brightness light curves with their fast/slow behaviour before and only slow behaviour after perihelion - may be both methods are not very precise when the comet is dim.

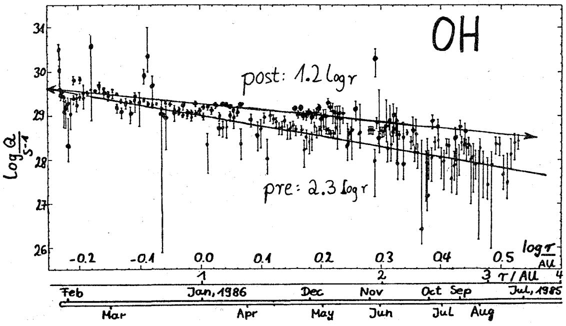

Figure 9. OH production of P/Halley from radio observations. Adapted from Ref. 25.

3.2.3 OH radio observations with the NRAO 43m antenna. Schloerb et al. (Ref. 26) derived their OH prod. rates from the 1667 MHz transition but applied their "Radio Model 1986a" (Fig. 10). As their data points are rather scarce the significance of the formulae

$$\log Q_{OH,pre} = 29.3 - 2.1 \log r \tag{16}$$

$$\log Q_{OH,post} = 29.3 - 2.2 \log r \tag{17}$$

is not known. While (16) confirms (8) and (12), (17) grossly contradicts (9) and (13) which may mean that four data points are not enough to pin down a trend with certainty (see sect. 3.1). Thus we only convert (17) into

$$\log Q_{OH,pre} = 30.2 - \underline{0.21}\ m \tag{18}$$

3.2.4 OI production from CCD spectrophotometry. Spinrad et al. (Ref. 27) used long slit CCD spectrophotometry to measure the production rate of atomic oxygen (Fig. 10). Here the 'usual' trend, more production at the same heliocentric distance outbound than inbound, is apparent once again, yielding

$$\log Q_{OI,pre} = 28.3 - 2.8 \log r \tag{19}$$

$$\log Q_{OI,post} = 28.5 - 2.0 \log r \tag{20}$$

which converts into

$$\log Q_{OI,pre} = 29.5 - \underline{0.29}\ m \tag{21}$$

$$\log Q_{OI,post} = 29.6 - \underline{0.29}\ m \tag{22}$$

The fact that (21) nearly = (22) is surprising but the scarcity of data does not allow a conclusion.

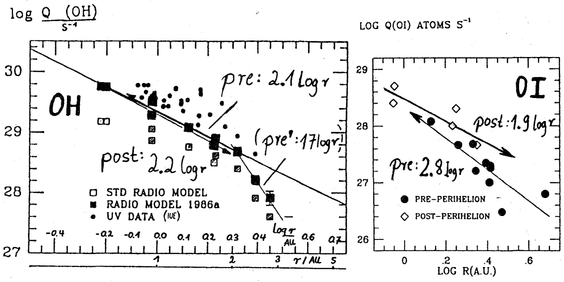

Figure 10. The production rates of OH, derived with Schloerb et al.'s "Radio Model 1986a" (Ref. 26) and of OI, determined by Spinrad et al. (Ref. 27)

3.3 Results for C_2 and CN

Unfortunately for these molecules - including C_2 which is most important in the visible part of the spectrum - useful data are available only for the preperihelion time, so far. Even there, the two available studies contradict each other.

3.3.1 Observations on McDonald Observatory using an Intensified Dissector Scanner spectrograph on the 2.7m-telescope by Cochran et al. (Ref. 28) were transformed into production rates using the Haser model. The preperihelion fit for C_2 is

$$\log Q_{C_2} = 27.1 - 4.2 \log r \tag{23} \rightarrow$$

$$\log Q_{C_2} = 28.9 - \underline{0.44}\ m \tag{24}$$

For CN the best fit is

$$\log Q_{CN} = 27.0 - 4.5 \log r \tag{25} \rightarrow$$

$$\log Q_{CN} = 29.0 - \underline{0.47}\ m \tag{26}$$

3.3.2 Photoelectrical photometry at the 91cm-telescope of the Catania Astrophysical Observatory by Catalano et al. (Ref. 29) through IHW standard filters provided gas production rates via the Haser model. The preperihelion result for C_2 is

$$\log Q_{C_2} = 27.0 - 3.5 \log r \tag{27} \rightarrow$$

$$\log Q_{C_2} = 28.5 - \underline{0.37}\ m \tag{28}$$

For CN Catalano et al find

$$\log Q_{CN} = 26.3 - 2.6 \log r \tag{29} \rightarrow$$

$$\log Q_{CN} = 27.4 - \underline{0.27}\ m \tag{30}$$

No consensus exists whether the larger coefficient of m compared with H_2O and its daughter has a physical meaning or is due to systematic errors in the last two studies. The common picture is that H_2O sublimation controls the production of all the other molecules. As stated in sect. 3.1 only a continuous in situ monitoring by a spacecraft may be able to provide a definitive answer.

3.4 Results for HCN : radio observations

Observations of the HCN J=1-0 rotational transition at 3.4 mm wavelength by Schloerb et al. (Ref. 30) with the Five College Radio Astronomy Observatory 14 m antenna yielded an extensive coverage of a parent molecule. The preperihelion result (4 obs.):

$$\log Q_{HCN,pre} = 26.6 - 2.8 \log r \qquad (31) \quad \rightarrow$$

$$\log Q_{HCN,pre} = 27.8 - \underline{0.29}\ m \qquad (32)$$

The postperihelion result, based on 10 observations:

$$\log Q_{HCN,post} = 26.8 - 2.0 \log r \qquad (33) \quad \rightarrow$$

$$\log Q_{HCN,post} = 27.6 - \underline{0.21}\ m \qquad (34)$$

(32) and (34) are broadly consistent with the OH and H_2O results discussed in sect. 3.2, with Q_{HCN} being lower by a factor of about 1000. It remains to be explained why the Q_{CN}-result (26) is so different while (30) is nearly the same formula as (32).

4. TENTATIVE CONCLUSIONS

As few of the studies at hand extend well beyond 2AU and those which do contradict each other, we shall restrict our discussion to the inner part of Halley's orbit, between November 1985 and May 1986. This makes it impossible to discuss the mechanism underlying the change of slope in the visual magnitude estimates at r = 1.7 AU with Halley inbound and the lack of any change of slope with the comet outbound. The inbound change of 'reactivity' n might be explained as proposed by Delsemme (this conference), its constancy after perihelion cannot.

While the generally enhanced production of Halley and resulting brightness after perihelion is consistent with Weissman's 'nuclear seasons' (Ref. 31), the extent of brightness enhancement is not (Weissman, this conference). The current debate on the correct rotation/precession/nutation of the nucleus may finally solve this riddle - the importance of understanding Halley's rotation has become clear in this respect.

The most surprising result of this study were the different coefficients of m before and after perihelion, dropping by about 30% for the most complete samples (sect. 3.2.1, 3.2.2 and 3.4). Provided that this is not the result of hidden systematic errors, the reason must be in the factors that justify the existence of a log Q = c - d m law (Ref. 32).

According to Festou, c and d should be constant for all comets when

1) steady state is established in the coma,
2) the ratio of C_2 (making all the visible light) and OH production rates does not vary and
3) the visible part of the spectrum is dominated by C_2 emission. Then the equation should read

$$\log Q_{OH} = 32.04 - \underline{0.4}\ m \pm 0.16 \qquad (35)$$

Festou suggests (private communication) that point 3 is not fulfilled for P/Halley in that <u>sunlight reflected by dust</u> contributed significantly to the total magnitude. As this effect makes the coefficient of m smaller, it may be the answer. In turn, our findings should indicate an enhancement of dust production after perihelion, depressing the coefficient still further. The incorporation of dust production into the understanding of total cometary magnitudes remains a task to be solved.

5. OUTLOOK

To know the gas and dust production of a comet can be of considerable importance. E.g., one wants to know at which rate the dozens of comets that approach the sun every year contribute to the interplanetary medium. Also, the knowledge of production rates is essential in calculating nongravitational parameters (Krasnopolsky, this conference). It should now be clear that <u>two considerable problems</u> are to be solved before the production rates of any comet can be calculated from magnitude observations alone:

- considerable underestimates of total magnitudes were typical in the past decades and centuries, and even today one can be misled by several magnitudes when incorrect visual magnitude estimates are taken at face value;
- the transformation of total magnitudes into production rates is more difficult than the single Eq. 35 in Ref. 32 might suggest. A further calibration with other well-studied comets - including dust-rich ones - is necessary.

6. ACKNOWLEDGEMENTS

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