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MAPS OF THE EMISSION OF CN AND OTHER MOLECULAR SPECIES IN THE SPECTRUM OF COMET HALLEY

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RESUMEN. Presentamos mapas de isolineas de la distribución espacial del flujo emitido por transiciones de algunas especies moleculares en el espectro del cometa Halley cuando se encontraba a una distancia del sol de 1.92 U.A., después del perihelio. Las observaciones se realizaron en el Observatorio del Roque de los Muchachos, en La Palma, con el telescopio de 2.5m, Isaac Newton, usando el RGO Image Photon Counting System acoplado al RGO Cassegrain Spectrograph. Esta contribución forma parte de un programa más general donde se pretende estudiar los ritmos de produción de algunas especies y su variación con la distancia al sol. Para lo cual, hemos realizado espectroscopia multiposicional del cometa en el rango espectral visible, en un rango de distancias comprendido entre 1.5 y 5 U.A.

ABSTRACT. We present isophotal maps of the distribution of the flux emitted by transitions of various molecular species in the spectrum of Comet Halley at a heliocentric distance of 1.92 A.U., after perihelion. The observations were made at the Observatorio del Roque de los Muchachos, in La Palma, using the RGO Image Photon Counting System attached to the RGO Cassegrain Spectrograph. This contribution is a part of a more general program, which aims to study the production rates of a number of species and its variation with heliocentric distance. To this end, we have taken multiposition spectrophotometry of the comet in the visible, which extends over a range of heliocentric distances from 1.5 to 5 A.U.

Key words: COMETS-HALLEY — MOLECULES

I. INTRODUCTION

The molecules vaporised from the nucleus of a comet expand outwards to a certain mean distance which depends on their life-time and the conditions prevailing in the cometary atmosphere. The molecules dissociate into radicals, which continue expanding until they, in turn, dissociate into others. Cometary spectra gives us information on these dissociation products, on the parent molecules and on the physical processes that are in action. The physical quantities of interest are the production rate of the species and its variation with heliocentric distance. The production rate of the species can be calculated by determining the total luminosity in the line produced by one of its transitions. This should vary as r-2 with heliocentric distance if the evaporation of the molecules and their excitation mechanism were fundamentally due to absorption of sunlight. A departure from this rule, would indicate that we must think in terms of other mechanisms for excitation and the variation of conditions in the atmosphere of the comet. More information can be obtained if we know the spatial distribution of a given emission. Theoretically, the column density of the species determined along the line of sight of an expanding atmosphere of uniform particles should vary as 1/r against distance from the nucleus. A departure from this dependance would tell us of a non-uniform distribution of particles. The spatial distribution of a given spectral line, combined with a dissociation model, allows us to measure the scale length and production rate of the parent molecules.

The advance in instrumental technology which now provides detectors for spectrophotometry which have a linear response and may be easily calibrated photometrically and the anticipated arrival of Comet Halley, have allowed us to plan observations of the comet at

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various heliocentric distances over the range from 1.5 to 5 A.U. to obtain spectrophotometry in the visible, which is where transitions of the majority of molecules present in the coma of the comet can be found. The spatial distribution of these molecules, as well as its variation with heliocentric distance can give us a mine of information to the physical processes in the comet´s coma.

So far, we have provisionally identified over one hundred lines from twelve individual molecules in the comet. Our aim is to produce a definitive atlas of the distribution, at several epochs, of the maximum possible number of species and of individual transitions of those species in the coma of Comet Halley. In this contribution, we present maps of CN, C2,NH2 and CH,which were obtained from observations on May 20/21st, whilst the comet was at a heliocentric distance of 1.92 A.U. We also present integrated fluxes and plots of the variation in intensity of each of these lines, or bands, with distance from the nucleus, out to 1.5 arcminutes in the sky, which corresponds to a linear distance of 95000 Km from the nucleus.

II. PREVIOUS STUDIES

Very little two dimensional photometry has been done of the distribution of any of the major species seen in cometary spectra due to the lack of a reliable method of calibration of spectra recorded on photographic plates. However, with the advent of the Boksenberg IPCS and CCD spectroscopy, both of which show linear response and can be easily calibrated photometrically, multipositional spectrophotometry has now become a practical possibility.

Over twenty five years ago, Swings and Page (1950) classified the extent of the main species in Comet Bester (1947k) in the following order, from least to most extended: NH2; C3; OH; NH; C2 and CN . This still remains one of the most detailed published works. More recently, the extensive compilation of Newburn and Spinrad (1984) of CN in 17 comets was not aimed at yielding spatial information. Malaise (1976) showed spatial profiles across several cometary nuclei, whilst Combi and Delsemme (1980) presented CN profiles of Comet Bennett (1970II) and Comet West (1976VI) using long-slit spectra. Emission from the nucleus of Comet Bowell (1980b) in CN was obtained by A Hearn et al. (1984). Mateev (1984) reported a CN profile of Comet Bennett (1970II), whilst Prieto et al. (1986), published low spatial resolution mapping of the distribution of the 3883E line of CN and the 5100E C2 band.

Very little work has been done on the spatial distribution, even in one dimension of other principal species. Malaise (1976) obtained spatial profiles of CH in Comet Bennett (1970 II), which suggest that this species has a very short scale length and thus must be highly concentrated close to the nucleus. Whilst A´Hearn (1982) notes that C3, like CH, is also highly concentrated towards the nucleus, without citing specific observations.

Good quality profiles of the coma of comets P/Tuttle, P/Stephan-Oterma and P/Brooks 2 in the 6300E line of OI based on long-slit spectra have been published more recently by Fink and Johnson (1984). Most recently, high resolution maps of comets P/Giacobini-Zinner and P/Halley, in several emission lines, have been obtained by Rees and his collaborators (Rees, 1985, Private Communication). Similarly, CO+ has also been widely used for imaging (eg: Rees, 1985, Private Communication) and in this case is known to be principally found in the cometry plasma tail, Swings and Page (1950), as are N2+, Swings and Page (1950) and H2O+, Miller (1980). The other widely studied species is H. The Lyman-alpha cloud of a number of comets has been imaged from space eg: Tago-Sato-Kosaka (1969 IX) and Bennett (1970 II), Bertaux et al. (1973), Code et al. (1972).

III. THE OBSERVATIONS

Our observations were carried out using the Image Photon Counting System (IPCS) attached to the 235 camera of the 100 inch (2.5 metre) Issac Newton Telescope (INT), in "El Observatorio del Roque de los Muchachos" (henceforth "el Roque", for brevity), on the island of La Palma, Spain, as part of a coordinated program of observation of Comet Halley in the infrared and visible (see: Prieto et al. (1985); Prieto et al. (1986) and Garzon et al. (1986), for further details). A 300 line per millimetre, 138.5 E mm-1 (at the central wavelength of 5500E), grating was used, with a slit width of 2", giving a spectral resolution of about 3.6Å, and a range from 3430Å to 7598Å. The maximum possible slit length allowed by the system, 4 arcminutes, was used for all the observations, giving a format of 2044 pixels in the wavelength axis and 90 sections (lines) along the slit, giving a spatial resolution of about 2.7 arcseconds.

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Eleven spectra of the comet have been used in all, each with a standard exposure, 500 seconds. The diferential motion of the comet was calculated by linear interpolation of the Yeomans ephemeris, Yeomans (1983) which enabled us to track on the comet even when it was outside the field of view of the tv monitor. All the spectra were taken with the slit aligned W-E, normally at 10 arcsecond intervals, starting at and centred on the nucleus, out to 60 arcseconds north and south. Unfortunately, the short observational window meant that no observations could be taken at 50 arcseconds north and south, hence the gap in the data in these positions. Sky subtraction was carried out using exposures taken 3 and 8 degrees to the north of the comet, in a region thought to be free of extended cometary emission.

IV. REDUCTION OF THE DATA

Reduction of the observations was carried out at the IAC using PANDORA, a suite of computer programs originally designed in Groningen for use with the telescopes at Mount Stromlo and Siding Springs Observatories. These programs have been translated by the software support group at the Instituto de Astrofísica de Canarias from their original VAX versions, to work on the IAC´s Data General MV/10.000 Computer.

Photometric calibration was carried out with two observations of the sub-dwarf Ross 627, Oke (1974), taken before and after the observations of the comet. Comparison with later observations of the standard star GD190 shows that there was a change of less than 1% in the transparency of the atmosphere during the night. Information on dust extinction was provided by the astronomers on the Carlsberg Automatic Transit Circle, which is also based at "el Roque". This was combined with the standard atmospheric profile for La Palma to give the final calibration.

All spectra have been smoothed to their theoretical resolution (approximately two pixels on the IPCS) using a gaussian filter. This allows us to identify weaker lines with greater security as the level of background "noise" is greatly reduced by this procedure.

V. THE MAPS

In figure 1(a-d), we show contour maps of the emission in various transitions. These were mainly selected as those lines whose extent from the nucleus of Comet Bester (1947k) was commented on by Swings and Page (1950). A standard wavelength range for each line was determined by inspection of the individual spectra and this range was used as the delimiter of the line in all positions (Note- We mention below a practical difficulty in this method with respect to the CN 3883E line). In the case of CN, in which the continuum is "clean" and easily defined, a continuum flux was defined on each side of the line and the continuum subtracted from the line flux. We note here that the maps in Prieto et al. (1986), include the contribution of the continuum although, at the epoch of their observations, this is seen from their work to be very small, except very close to the nucleus. In other cases, where it is not possible to define with real confidence an underlying continuum, we have, in these initial data, decided to calculate fluxes including the continuum, accepting that the resultant maps do not necessarily show the distribution of the line flux, but instead, show the distribution in a combination of line and continuum fluxes.

Calculated fluxes were stored in a matrix and a standard contour plotting program was used to fit isophotes to the data. Maps are presented here of emission in CN (3883Å), CH (4225Å), C_2 (5100Å) and NH_2(6107Å). We also present profiles in C_3 (4040Å). It is immediately evident that only in CN and in C_2 is the emission extended over the entire area of the maps, in the cases presented here, 182"x80", with a data spacing of 10", in the declination axis. Maps were also prepared over an area of 182"x120", with a data spacing of 20", in the declination axis, but show no significant differences. This confirms the observations, previously noted in section I, that assign both these species a very high scale length. At the epoch of observation, with r, the heliocentric distance, 1.92 A.U., the theoretical radius of the CN coma, derived from its adopted scale length, A´Hearn (1982), is $1.1x10^6$Km. This converts to a projected radius in the sky of 18 arcminutes. An order of magnitude check on this figure is provided by subtracting out two sky exposures. When the

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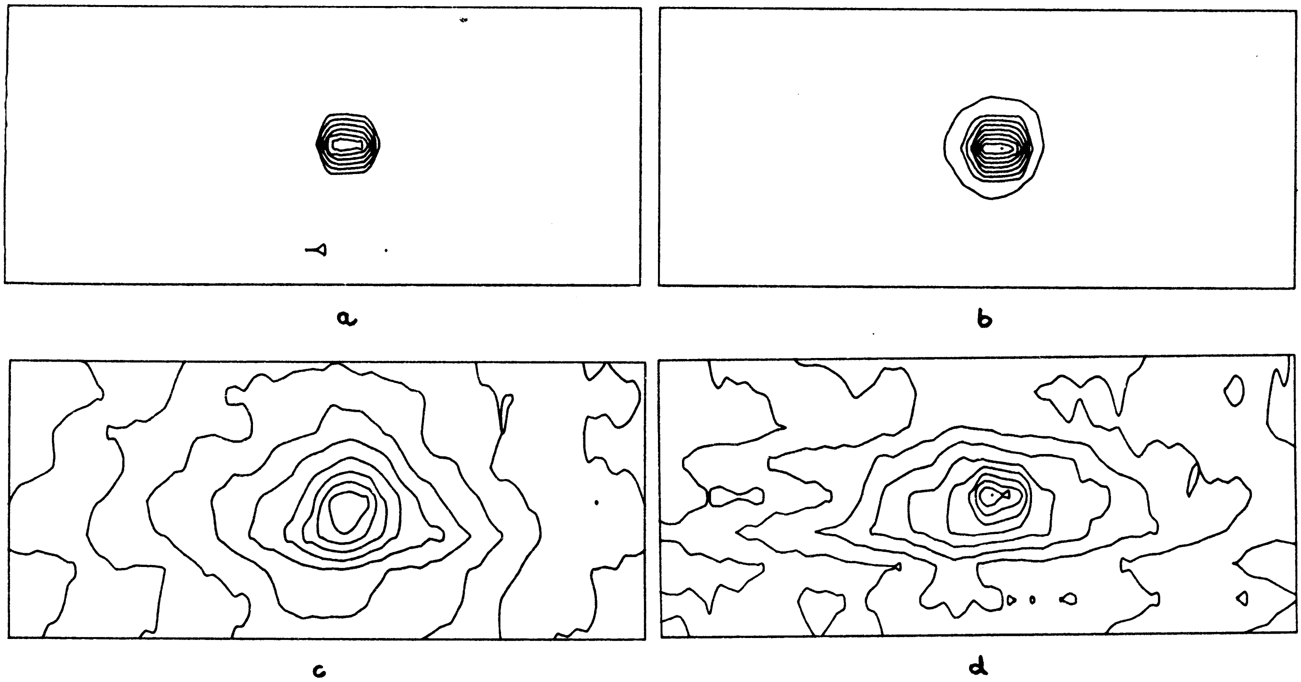

Fig. 1. (a-d). Maps in CH, NH_2, CN, C_2, of Comet Halley, produced by the method described in the text. All maps are 182"×80" with west to the left and south to the top and calculated for 5.2 arcsecond square sections of sky. Isophotes are equally spaced in all cases. In Table 1 we give the intervals between isophotes, the minimum flux plotted and the integrated flux out to the last plotted isophote.

exposure at 8´is subtracted from that at 3´; there is no evidence of extended CN emission in the resultant spectrum. Indeed, even at 3´north of the comet, there is no evidence of any emission at all from the comet. For C2, the theoretical radius and projected radius are 6.0x105Km and 10 arcminutes respectively. In contrast, the values for C3 are 2.2x105 and 3.4 arcminutes; those for NH2 and CH and are not known, but emission is thought to be highly concentrated close to the nucleus. In the latter two cases our maps show a highly concentrated emission, which is especially marked in NH2. Our data is still somewhat provisional, thus we must reserve judgement until a more detailed analysis, now in progress (Kidger et al., 1986, In preparation), is completed.

TABLE 1.

PARAMETERS FOR THE MAPS

LINE OR BAND	INTERVAL Ergs/s/cm2/Å	MINIMUM FLUX Ergs/s/cm2/Å	INTEGRATED FLUX Ergs/s/cm2/Å
CH	8.6x10-15	1.55x10-16	4.52x10-13
NH_2	8.3x10-15	3.77x10-15	1.59x10-12
CN	2.3x10-14	5.49x10-15	1.78x10-10
C_2	3.8x10-14	1.26x10-14	3.14x10-10

We do not see anything in the presented maps which is consistent with small-scale structure. However, we reserve the possibility that the further treatment of the data, which is currently in progress, may show currently invisible inhomogeneities in the distribution of emission.

In figure 2(a-e), we present profiles of each of the lines as shown by flux against distance from the nucleus, for a single exposure crossing the nucleus in Right

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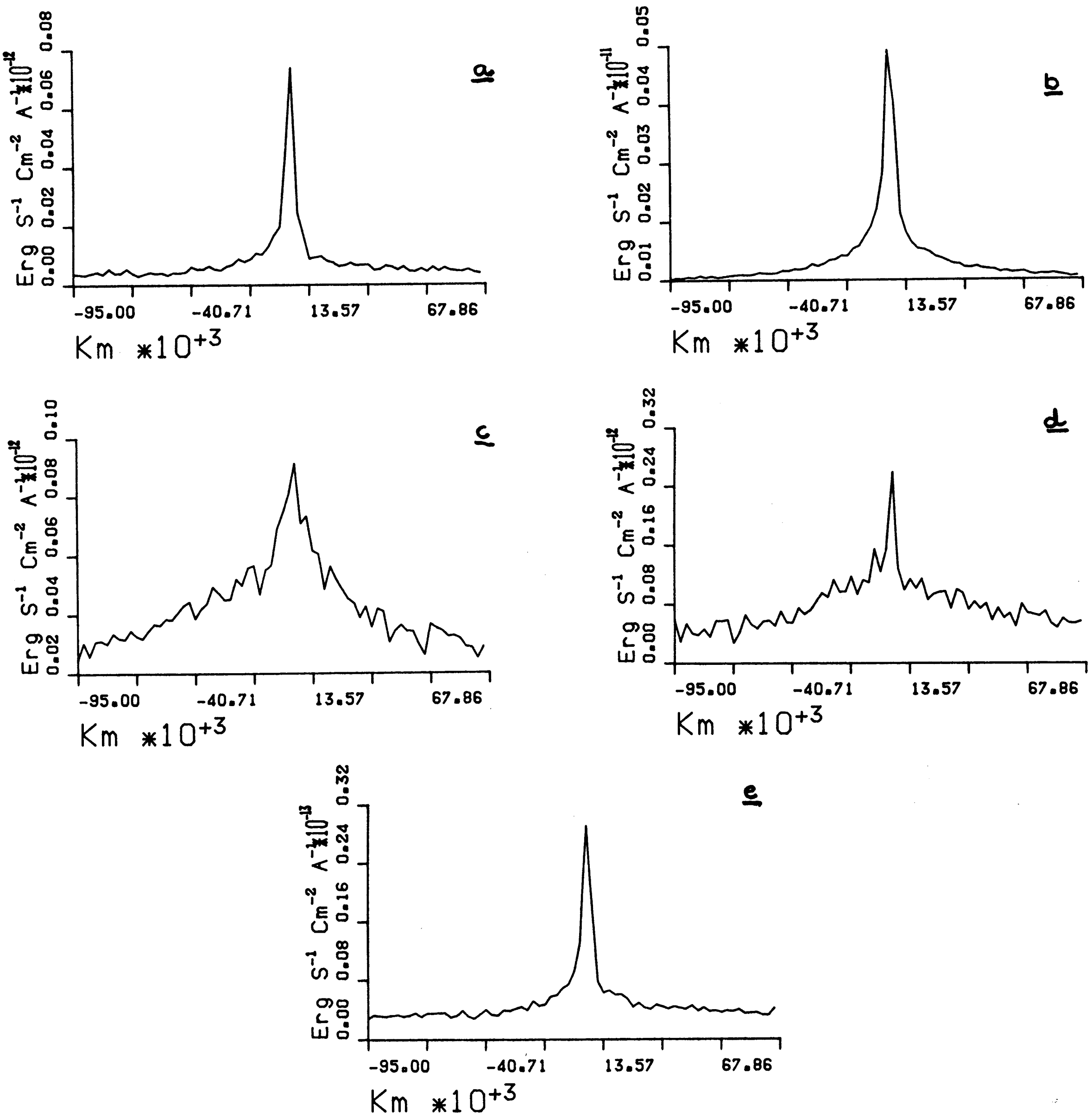

Fig. 2. (a-e). Profiles of the flux distribution in NH_2, CN, C_2 and CH as a function of distance from the nucleus. The negative direction is west and the positive east.

Ascension. We note that there is some vignetting present at the edge of the field, hence here, as in the maps, only the central 3 arcminutes of the data were used. We also note that the fall-off observed in the CN (3883Å) line (the only line from which we have, until now, subtracted the continuum) does not follow the expected 1/r law, but instead falls as a higher power of r. This is inconsistent with a uniform distribution of particle cross-sections in a slowly expanding coma and we note that this is similar to the behaviour of Comet Bowell (1980b), Johnson, Fink and Larson (1984).

VI. THE CASE OF CN

A practical difficulty was encountered with the 3883E line of CN. This line is the most prominent in the spectrum and also one of the best studied. We note though that its

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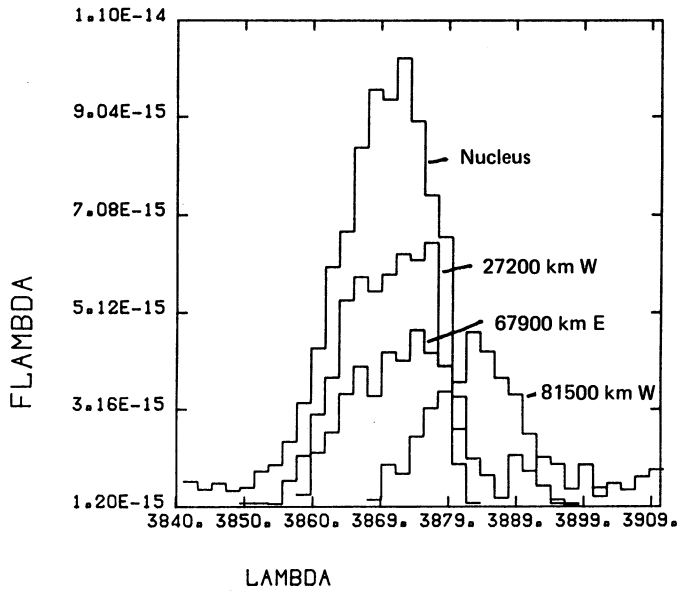

FIGURE 3. Profiles of the CN line at four positions within the coma.

position and morphology do not remain constant within a single spectrum, even over as little as 20 arcseconds. In figure 3, we show profiles of the CN line taken at different distances from the nucleus of the same exposure. Successive positions are: (1) 81500Km west; (2) 27200Km west of the nucleus; (3) the nucleus and (4) 67900Km east of the nucleus. In all the profiles furthest to the west of the nucleus, the CN line is indeed seen in 3883Å. However, the profile at 27200Km west clearly shows the line at 3870Å, which is the approximate position that is keeps in the rest of the profiles. We note also that the structure of the profile changes, changing from a double peaked line, with one component clearly larger, to a flat-topped profile and then to a double peak.

Initially we were suspicious of the reality of this sudden shift in wavelength, suspecting some artifact of calibration. Tests on features in the sky spectra (in which the continuum is rather "cleaner" than the cometary spectra and thus somewhat easier to measure), do not show this shift, which must thus be attributable to the comet. It is well known that the CN 3883Å line shows the Swings effect strongly, this effect being very sensitive to heliocentric velocity, hence the wide variety of structure that the CN line shows in the spectra of different comets. We thus interpret the shift in the line as being due to a local velocity field within the comet, with material within this part of the coma having a different relative heliocentric velocity to the bulk of the coma. At the present, it is not clear how velocities can be measured by using this effect, but we are currently investigating the possibilities.

VII. CONCLUSIONS

We believe that we have demonstrated the potential of multiposition spectrophotometry of comets using an IPCS system as detector, although some problems still have to be solved by careful re-analysis of the data. We have obtained maps in CN, C2, NH2 and CH and profiles in the same molecules and also Ç3. The results are consistent with the current state of knowledge of the scale lengths of the molecules concerned. A further, and unexpected result is that our profiles of the CN line may have revealed a method of measuring local velocity fields in the comet, by means of the Swings effect, although problems remain in its application.

By an analysis similar to the one performed here, of data obtained on different dates and hence at different heliocentric distances, we hope to obtain information on the scale lengths and production rates of a large number of individual atomic and molecular constituents of Comet Halley and to obtain useful bi-dimensional distributions for up to one hundred individual transitions. The latter will aid in revealing the relative population levels and hence quantum mechanical processes going on in individual species.

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