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LETTER

Letter to the Editor

Chemistry of Protosolar-like nebulae:

The molecular content of the DM Tau and GG Tau disks

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Abstract. We report the detection of CN, HCN, HNC, CS, HCO^+, C_2H and H_2CO (ortho and para) in the protoplanetary disks of DM Tau and GG Tau. For the first time organic molecules are observed in objects representative of the presolar nebula. These molecules are underabundant with respect to the standard dense clouds. The depletions in the "outer" disk of DM Tau ($100 < r < 900$ AU), derived from the line intensities and state of excitation, range from $f \simeq 5$ (for CO) to 100 (for H_2CO). The relatively large abundances of CN and C_2H are typical of a photon-dominated chemistry.

Key words: Stars: T Tauri – binaries: close – circumstellar matter – pre-main sequence – Radio-lines: stars

1. Introduction

Observing the molecular composition of the protosolar nebula is an old, but impossible dream. Yet, in some way, this dream is becoming true: recently, astronomers have uncovered dusty disks around a number of low-mass pre-main sequence stars (Beckwith et al. 90, B90) and, thanks to large gains in sensitivity at mm wavelengths, we are about to learn the composition of these disks. Chemical surveys have already been performed in low-mass star forming regions (e.g. NGC1333, Blake et al. 1995). All of them trace the early stages of star formation and therefore are not representative of physical properties encountered in protoplanetary disks around older TTauri stars.

The observation of circumstellar disks is not easy, due to their small sizes and to confusion with foreground and background gas. It is thus important to select the right objects: as close to us as possible, old enough to have escaped from their parent cloud, but young enough to be still surrounded by large optically thick disks.

The T Tauri stars DM Tau and GG Tau fit the above criteria. Distant by only 140 pc, they are located at the edge of the L 1551 core, in a region devoid of CO emission; they show no evidence of outflowing molecular gas. DM Tau is one of the oldest T Tauri stars in the Taurus region (its age is $\sim 5\,10^6$ yr and its mass $M_* = 0.65 M_\odot$, according to Mazitelli's tracks –1989). An extended disk of molecular gas was discovered by Guilloteau & Dutrey 94 (GD94). Its radius is $R_{out} \simeq 6''$ (800 AU). Continuum and ^{12}CO J = 1 → 0 maps, made with the IRAM interferometer at angular resolutions of 1.2″ and 2.5″ (Guilloteau et al. 1996,G96), show a compact dust disk of radius $R_d \simeq 0.6''$ (80 AU) at the center of the CO disk. The mass of gas associated with the dust disk is $M_d \sim 0.03\,M_\odot$, assuming a dust absorption cross section $\kappa_d(\nu) = 0.1 \times (\nu/10^{12}\mathrm{Hz})^{-1}$ cm^2/g (B90).

GG Tau is a young binary star ($5\,10^5$yr) surrounded by a CO disk of radius $R_{out} \simeq 6''$ (800 AU) which has been centrally cleared by tidal interactions up to a radius $R_{in} \simeq$ 180 AU (Dutrey et al. 1994, DGS, Roddier et al. 1996). ^{13}CO interferometric observations show that the disk rotates with a Keplerian law around a central object with $M_* \sim 1.2$ $M_\odot$. The gas mass of the disk is $M_d \simeq 0.15 M_\odot$ (DGS).

The large masses derived from dust imply high densities near the stars and, presumably, large molecular depletions. Molecules may also be depleted in the cold outer parts of the disks, the mass of which may be larger than indicated by CO line strengths. Molecular excitation offers an alternate way to assess the outer disk masses. We have thus studied the molecular emission in DM Tau and GG Tau and interpreted the observations in terms of gas densities and molecular depletions. The knowledge of the depletions in two objects issued from the same cloud but following different evolution paths may help to understand the evolution of the disks; at stake is the formation of planets.

2. Observations and Results

The observations were made between June 1994 and Aug. 1996 with the IRAM 30-m telescope. We observed in the wobbling mode with a beamthrow of 60″. Three receivers and a splittable correlator were used to observe simultaneously several molecular transitions. The receivers were tuned single-sideband, with

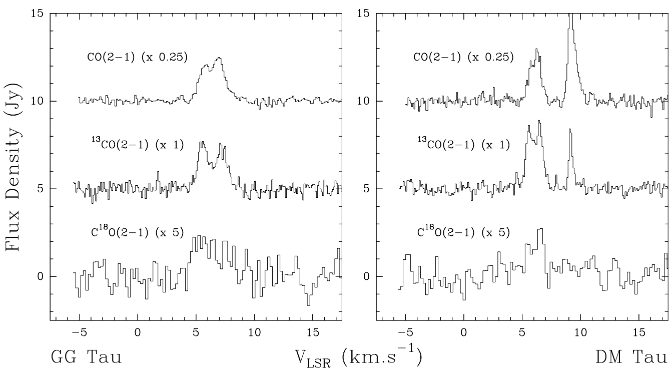

Fig. 1. Line profiles of the main CO isotopomers, observed toward GG Tau and DM Tau. The $C^{18}O$ J = 2 → 1 spectra required each 8 h of integration (*on* + *off*). The double-peaked profiles are characteristic of tilted disks in Keplerian rotation.

USB rejections $>$ 10 dB at 1.3 mm and 2 mm, and $>$ 25 dB at 3 mm (checked on Orion-IRC2 and IRC+10216). The atmospheric water vapour content was 1.5 − 5 mm. Frequent pointing and focussing checks insured pointing errors $< 3''$ (r.m.s.).

We have surveyed more than 40 strong transitions from 28 different molecules and isotopomers. The line profiles of the main CO isotopomers are shown in Fig. 1; the other most significant profiles in Fig. 2 and 3. The corresponding integrated intensities are listed in Table 1. Since the sources are smaller than the beam, we have expressed the intensities in units of flux, rather than of temperature, using Mars and Saturn as flux calibrators. The intensity scale is accurate to $\leq$ 15%. Upper limits to the other line intensities will be reported elsewhere.

In addition to carbon monoxide, we have detected 7 molecular species: CN, H_2CO (ortho and para), CS, HCO^+, HCN, HNC and C_2H.

Whereas the ^{12}CO lines are thermalized and optically thick throughout the disks of DM Tau and GG Tau, the lines of the rare $C^{18}O$ isotopomer are optically thin, except, may be, very close to the star. In the optically thin case, the flux integrated over the line is $S = B_\nu(T_{ex})/D^2 \times \kappa\, x(C^{18}O)\, M_g$, where T_{ex} is the excitation temperature, κ the absorption coefficient per gram of molecule μ and $x(\mu)$ its fractional abundance relative to H_2. For an optically thick Keplerian disk with a central hole, moderately inclined on the line of sight, the integrated flux is:

$$S = B_\nu(T_{ex})(\rho\delta v)/D^2 \times \pi(R_{out}^2 - R_{in}^2)\cos i \qquad (1)$$

where R_{in} and R_{out} are the inner and outer radii, δv is the local turbulent velocity (around 0.1-0.2 km.s^{-1}) and ρ is a geometrical factor of order $\sim$ 1.5 (G96).

The species other than ^{12}CO are expected to have an intermediate behaviour: as the H_2 surface density varies by several orders of magnitude between the center and the edges of the disks, their lines are likely to be optically thick near the center and optically thin near the edges. The value of the parameter R_{out} derived from Eq.1 gives then a first estimation of the radius R_1 at which τ = 1 (in fact, an upper limit to R_1 if the line is thermalized) and a lower limit to the outer radius of the source.

We have listed in Table 1 (col 5 & 14) the values of R_{out} calculated for the most significant lines by assuming $T_{ex} = T_k$. Following GD94 and DGS, we used for both sources D = 140 pc, $\rho\delta v$ = 0.3 km.s^{-1} and adopted R_{in} = 0 AU, T_k = 20 K, i = 35° for DM Tau and R_{in} = 180 AU, i = 43°, T_k = 15 K for GG Tau.

In the case of DM Tau, we have also interpreted the line intensities in the classical framework of a geometrically thin disk in hydrostatic equilibrium (B90), with a surface density $\Sigma = \Sigma_0(r/r_0)^{-p}$ and a gas temperature $T_k = T_0(r/r_0)^{-q}$. We assume here p = 1.5 and, for simplicity, q = 0 (Dutrey et al. 1996, GD94). Since the ^{12}CO J = 2 → 1 line is optically thick throughout the disk, we used the outer radius R_{out} deduced from ^{12}CO as a realistic value of the "true" outer radius $R_{ext} \simeq$ 800 AU. The model yields R_1 (col 6). The large value of R_{out} found for ^{13}CO and the relatively small R_{out} found for $C^{18}O$ imply for standard interstellar isotopic abundances ($x(^{13}CO)/x(C^{18}O)$ = 7) that the exponent p is $<$ 2. Similarly, our detection of CS and HCO^+ and our non-detection of $C^{34}S$ and $H^{13}CO^+$ imply $p < 2 - 2.5$. Thus, the actual surface density profile in the "outer" disk ($r >$ 100 AU) cannot be much steeper than the classical profile $\Sigma \propto r^{-1.5}$ adopted here.

We stress that, even though we reached for most lines an unprecedently low detection level, because of beam dilution our data are not sensitive to the *inner* disk within 100 AU from the star. This is roughly the size of the dust disk, hence direct comparison of masses derived from dust and molecular emission are not possible in DM Tau.

3. Density and abundances

In DM Tau, the values of R_{out} and R_1 calculated for most of the lines of Table 1 are small compared to the ^{12}CO radius of 800 AU. This suggests that the lines are optically thin in the outer disk and that it is possible to derive molecular abundances. This, however, supposes that the lines are thermalized and/or that the gas density is known. The latter can be determined neither from the dust thermal emission, which is too weak to be detected outside R = 200 AU, nor from the CO line intensities, since CO may be depleted (only crude limits can be set using these tracers). On the other hand, assuming that the gaseous disk is in hydrostatic equilibrium and that the fractional abundances $x(\mu)$ are constant, our data can be used to bracket the gas density and mass.

Due to the flaring of the disk, the volume density profile ($n(r) \propto r^{-3}$) is twice steeper than Σ, so that the high excitation lines may not be thermalized at large radii. The measurement of the radius R_c at which the critical density n_c (col 3, defined by $T_{ex}(n_c) = T_k/2$) is reached, further constrains the density model. The H_2 density in the equatorial plane is

$$n(r) = 10^5\, f(\mathrm{CO})(r/500\mathrm{AU})^{-3}\mathrm{cm}^{-3} \qquad (2)$$

where $f(\mu)$ is the average depletion of molecule μ, hence $f(\mathrm{CO}) = 1.4\,10^{-7}/x(C^{18}O)$ (the average densities along the line of sight are expected to be about twice lower). CO J = 2 → 1 is undoubtly thermalized until the edge of the disk and the lines

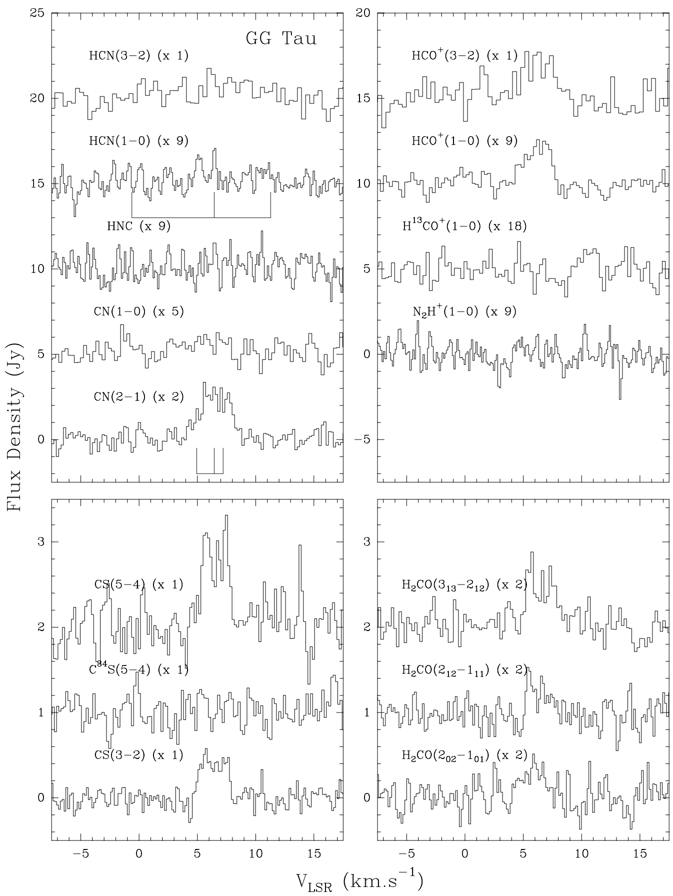

Fig. 2. Line profiles observed toward GG Tau. Integration time (*on* + *off*) is 4–8 h for each spectrum. Double-peaked profiles are observed for H_2CO 3_{13}–2_{12} and CS 3–2 and 5–4. They agree in position and width with the CO line profiles. Hyperfine components of HCN and CN are indicated.

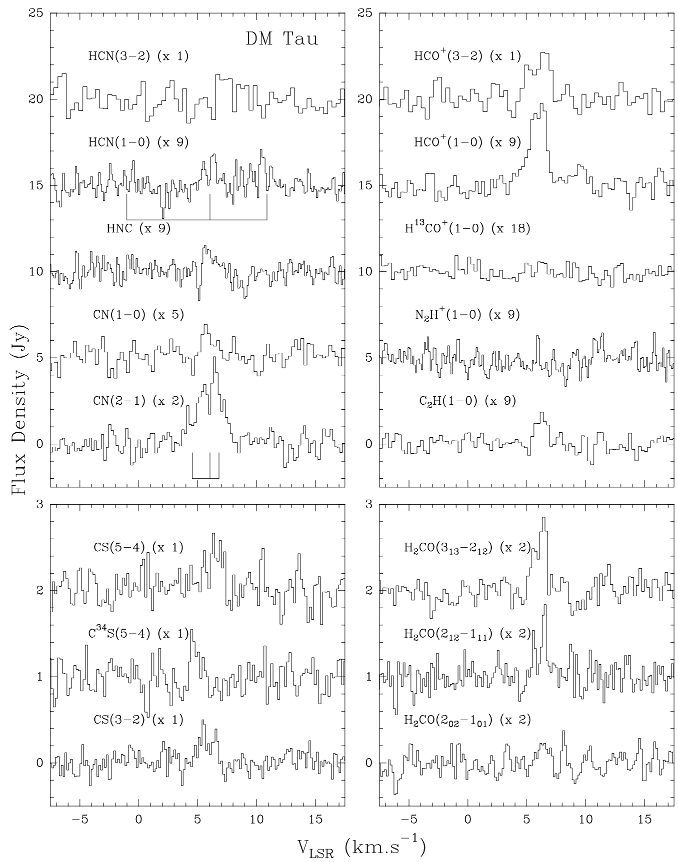

Fig. 3. Same as Fig. 2 for DM Tau.

with $n_c \simeq 10^5$cm^{-3} at least up to r = 500 AU. The state of the high J lines of CS, CN, HCO^+ and HCN depends on f(CO).

First, we note that R_c must be $\geq R_{out}$ in all cases. Indeed *i)* T_{ex} is expected to drop sharply for $r > R_c$ and *ii)* for optically thin or subthermally excited lines, we have $(1-e^{-\tau})T_{ex} < T_k$. In our p = 1.5 model, assuming T_{ex} = T_k up to R_c and T_{ex} = 0 beyond, we actually derive $R_c \simeq (R_{out}^2 + 3R_1^2)^2/(16R_1^3)$, which is $> R_{out}$. Now, R_{out} = 360 AU for the CN J = 2 → 1 line, so the critical density $n_c \simeq 10^6$ cm^{-3} must already be reached at this radius. However, for f(CO) = 1, R_c (col.7) is smaller. To obtain at least R_c = R_{out}, it follows from eq.(2) that f(CO) $\geq$ 5. This minimum value is strengthened by the hyperfine component ratios of the CN J = 2 → 1 line, which imply optically thin emission and preclude radiative excitation.

Conversely, in DM Tau, the values of R_1 and R_{out} are smaller for the HCO^+ J = 3 → 2 line than for the J = 1 → 0 line. This implies that the J = 3 → 2 line is subthermally excited and that $n \leq 10^6$ cm^{-3} beyond r = 400 AU. Then, f(CO) $\leq$ 8. Such a value is consistent with the upper limit obtained for HCN J = 3 → 2 .

The photodissociation of CO at the edge of the disk provides a rough, but independant way to estimate f(CO). In a dense cloud exposed to the unshielded IS radiation field, CO is largely photodissociated at depths $\tau_v < 0.7$, or hydrogen column densities $N_{H_2} < 7\,10^{20}$ cm^{-2} (see the calculations of van Dishoeck and Black 1988, which assume a "normal IS" τ_v/N_{H_2} ratio, and the measurements of Cernicharo and Guélin 1987). Setting the photodissociation radius R_{phot} = 900 AU yields f(CO) $\simeq$ 4 at this radius. Note that the value of $N(H_2)$ at R_{phot} should not be sensitive to the dust grain properties, since the CO shielding is dominated by H_2.

Most likely in DM Tau, f(CO) $\simeq$ 5 on the average, and the mass of the disk visible in $C^{18}O$ is close to $M \sim 4\,10^{-3}\,M_\odot$ (the value calculated for p = 1.5). It is close to the "minimum mass" of the classical solar nebula models.

Having determined the mass M and shown that the low J lines are thermalized and optically thin, we can readily derive the average molecular abundances $x(\mu)$. Those are listed in col. 9 of Table 1, together with the average molecular depletions $f(\mu)$ (col. 10). The latter were calculated with respect to the TMC 1 abundances listed in col. 11. The low angular resolution and relatively low S/N ratios do not allow to investigate the radial abundance variations predicted by Aikawa et al. , 1996. We find that CO is underabundant by a factor of $\simeq$5, CN, HCO^+ and C_2H by factors of 10, and CS, HCN, H_2CO and HNC by factors $\geq$30. The large $C^{18}O$/CS ratio (100), the non-detection of SO

Table 1. Integrated line intensities and disk parameters derived for DM Tau and GG Tau.

Molecular Line		n_c cm^{-3}	DM Tau S_ν Jy. km$\cdot$s^{-1}	R_{out} AU	R_1 AU	$R_c^{(1)}$ AU	$R_c^{(5)}$ AU	$x(\mu)$	f(μ)	TMC1 $x(\mu)$	GG Tau S_ν Jy. km$\cdot$s^{-1}	M_D M$_\odot$	ΔR AU
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
^{12}CO	2-1	3 10^3	14.9(0.4)	780	660	1590	2710	1.4(-5)		7.0(-5)	21.5(1.6)	2.0(-4)	1050
^{13}CO	2-1	3 10^3	5.40(.13)	500	250	1590	2710	3.3(-7)	3	1.0(-6)	5.82(.19)	2.5(-3)	520
C^{18}O	2-1	3 10^3	.68(.07)	180	50	1590	2710	3.0(-8)	5	1.4(-7)	1.08(.10)	5.1(-3)	160
HCN	1-0	2 10^5	.38(.05)	220	65	390	670	5.5(-10)	40	2 (-8)	.50(.07)	3.2(-3)	180
	3-2	4 10^6	<1.9	<260		145	250				2.8(.7)	9.1(-4)	260
HNC	1-0	2 10^5	.16(.03)	200	55	390	670	2.4(-10)	90	2 (-8)	<.15	<2.5(-3)	<120
CN	1-0	3 10^5	1.38(.24)	230	70	340	580	3.2(-9)	10	3 (-8)	1.44(.32)	2.7(-3)	170
	2-1	10^6	8.7(0.4)	360	140	230	390	2.5(-9)			8.4(0.4)	2.6(-3)	310
CS	3-2	3 10^5	.47(.07)	210	65	340	580	3.3(-10)	30	1 (-8)	1.2(.07)	7.6(-3)	290
	5-4	10^6	.67(.11)	160	45	230	390	1.7(-10)			2.55(.20)	1.6(-2)	270
C^{34}S	5-4		.38(.11)	120	23	230	390	<8(-11)	>6	5 (-10)	<.45	<6.3(-3)	<70
H$_2$CO	2_{12}-1_{11}	10^5	.30(.04)	180	50	490	840	5(-10)	50	2(-8)	.34(.05)	3.0(-3)	120
	2_{02}-1_{01}	2 10^5	.11(.04)	105	23	390	670	2(-10)	100		.42(.06)	1.1(-2)	130
	3_{13}-2_{12}	5 10^5	.48(.04)	160	40	290	490	2(-10)	100		.79(.06)	5.9(-3)	130
HCO$^+$	1-0	6 10^4	.82(.04)	450	200	590	1000	7.4(-10)	11	8 (-9)	.67(.04)	1.6(-3)	350
	3-2	10^6	4.1(.5)	370	150	230	390	1.2(-10)			6.7(.9)	5.2(-3)	470
H^{13}CO$^+$	1-0	6 10^4	<.06	<120		590	1000	<3.6(-11)	>3	1.1(-10)	<.09	<4.9(-3)	¡80
C$_2$H	1-0	2 10^5	.55(.08)	240	80	390	670	1.1(-8)	7	8 (-8)	<0.55	<3.2(-3)	<180
N$_2$H$^+$	1-0	7 10^4	<.45	<220		560	950	<2(-10)	>2	5 (-10)	<0.70	<7.3(-3)	<140

Notes to Table 1: Col 4 & 12: line areas have been calculated for v = 6.05 km$\cdot$s^{-1} and Δv = 1.4 km$\cdot$s^{-1} in DM Tau and 6.40 and 2.45 km$\cdot$s^{-1} in GG Tau, the velocities and widths derived from the ^{13}CO J = 2 $\rightarrow$ 1 line profiles. The errors are 1σ, and the upper limits correspond to 3 σ. Col 7: $R_c^{(1)}$ is the critical radius when no CO depletion is assumed (f(CO) = 1). Col 8: $R_c^{(5)}$ is the critical radius for our model (f(CO) = 5). Col 11: abundances measured in TMC-1, adapted from Ohishi et al. 1992 and Cernicharo & Guélin 1987. Col 13: Masses computed using the abundances derived for DM Tau, and assuming optically thin emission. Col 14: ΔR is the width of the ring, $R_{out} - R_{in}$.

and H$_2$S, and the relatively large HCO$^+$ abundance suggest that sulfur and metals are depleted in the gas phase.

Although depletion appears as the dominant process, the large C$_2$H/HCO$^+$ ($\simeq$ 15) and CN/HCN ($\simeq$ 6) abundance ratios seem characteristic of photon-dominated chemistry: Lucas & Listz (1996, LL96) find ratios $\simeq$ 20 along the lines of sight with A$_v$= 1–2 mag., whereas models of irradiated clouds predict ratios of $\sim$ 10 at depths τ_v= 2. The low H$_2$CO/HCO$^+$ ratio seems also indicative of low extinction, H$_2$CO being difficult to form and easy to destroy in unshielded regions (see however LL96). Assuming normal dust extinction, our DM Tau model yields τ_v = 2 at $\sim$300 AU (where C$_2$H, CN and HCO$^+$ are observed), in good agreement with the above.

Despite its different morphology, rather similar conclusions can be reached for GG Tau. The detection of HCN J = 3 $\rightarrow$ 2 up to R = 440AU (ΔR = 260AU) confirms the presence of a very dense ring after $R \sim$ 180 AU, as already observed by DGS. We cannot deduce an upper limit of f(CO) but following DGS's density model, a lower limit can be obtained from the HCO$^+$ J = 3 $\rightarrow$ 2 line, yielding f(CO) $\geq$ 5 at $R \simeq$ 650 AU. This is still in agreement with the depletion factor of $\sim$ 20 deduced by DGS from comparison between the dust and CO distributions.

The above analysis shows that depletion must be accounted for when deriving masses from molecular column densities. Our best estimates for the *gaseous* mass of the *outer* disks of DM Tau and GG Tau are $\simeq 0.005 - 0.010\,$M$_\odot$. Hence, a significant gaseous reservoir is still available for planet formation even for the "old" TTauri star DM Tau. Although the masses come close to the "minimum mass" solar nebula, they are still small compared to dust derived masses. For DM Tau, this may be consistent with the dusty component being confined within $r <$ 100 AU. For GG Tau, the answer will depend on the effective width of the circumbinary ring: should this ring be larger than about 200 AU, the actual depletions in the ring must be much higher. Only interferometric images can provide clear answers to these problems.

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