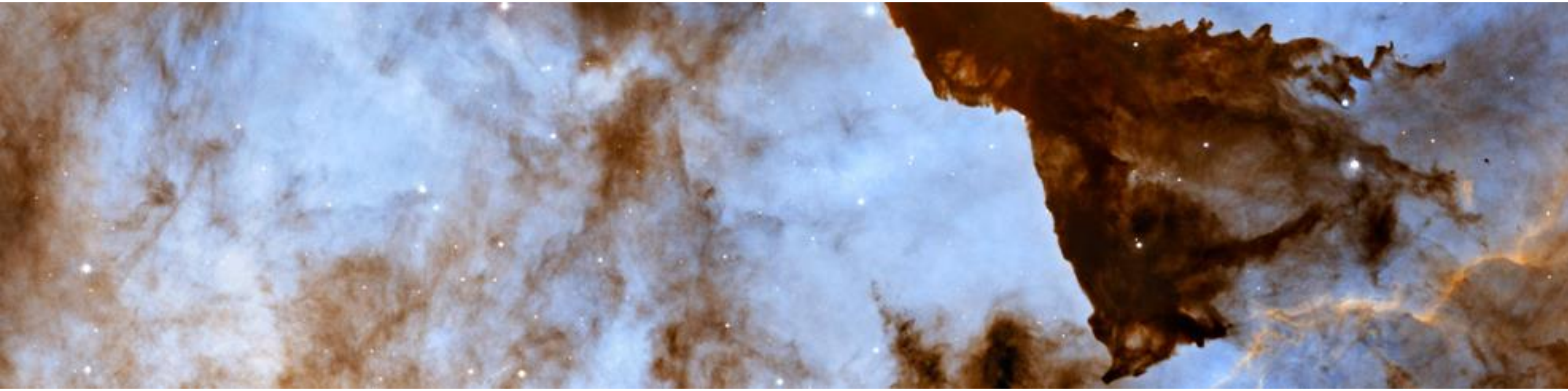
HLADNI MOLEKULSKI OBLACI



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Osobine

- najgušća vrsta MZM
- objekti sa sopstvenom gravitacijom
- veoma turbulentni
- prisutno magnetno polje
- akrecija na česticama prašine

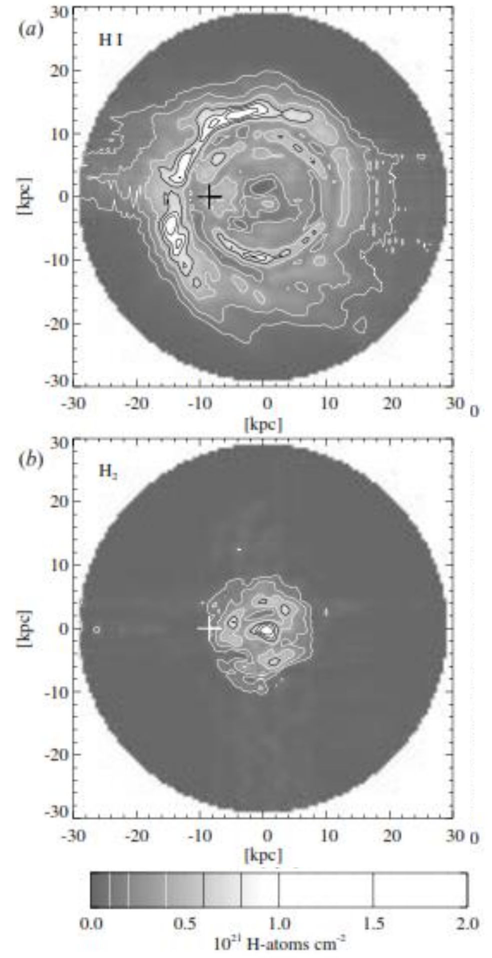
dominantan fizički proces?

	Veličina	*Masa i gustina*	*Predstavnici*	*Karakteristike*
Džinovski molekulski oblaci	Oko 50–120 pc	$\approx 10^6 \mathcal{M}_\odot$; $n \approx 10^2$–10^3 čestica po cm^{-3}	Orionov džinovski molekulski oblak, Maglina Orao	Detektovano je preko 100 različitih molekula
Mali oblaci, globule	Oko 1 sg	2–100 $\mathcal{M}_\odot$	Bokove globule	Okolina u H II regionima; sadrže H_2, CO i He i silikatne čestice
Difuzni vlaknasti oblaci	Do 100 pc	30 čestica po cm^{-3}	Infracrveni cirusi	Detektovani na velikim galaktičkim širinama - gusta, amonijačna jezgra.

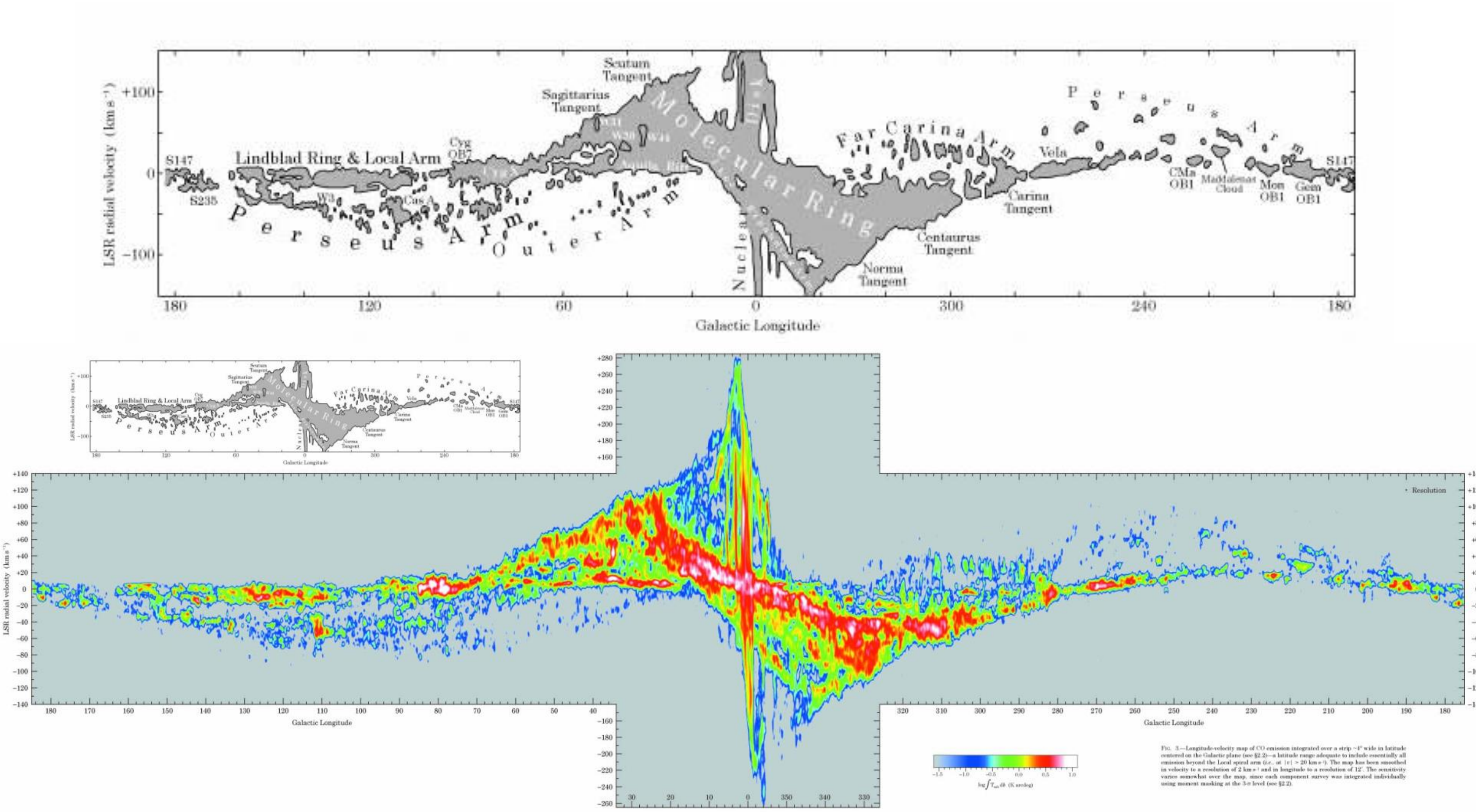
Prostorna raspodela MC

- zauzima manje od 1% zapremine međuzvezdanog prostora
  - između 3.5 i 7.5 kpc od centra Galaksije
  - disk debljine 50-75 pc
- položaj usko povezan sa spiralnim granama
  - protivi se teoriji disocijacije (t<10^6 god)

Hunter et al.

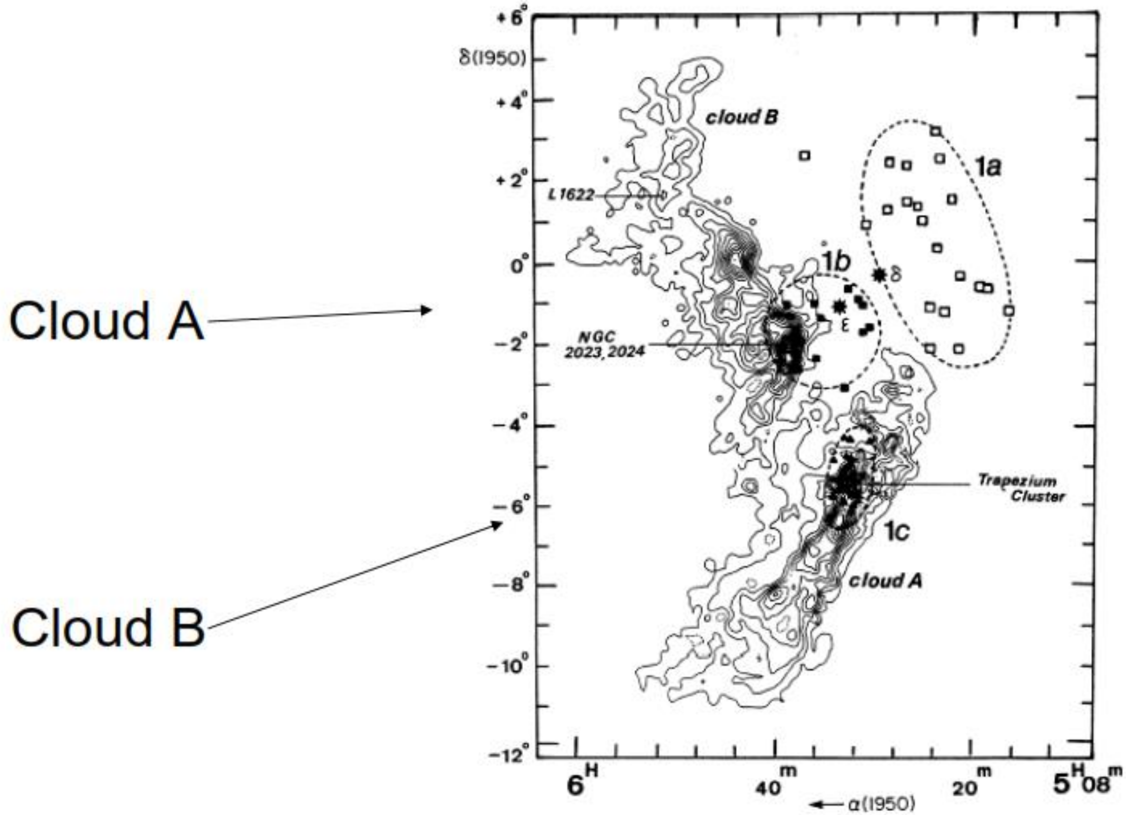


CO mapa naše Galaksije

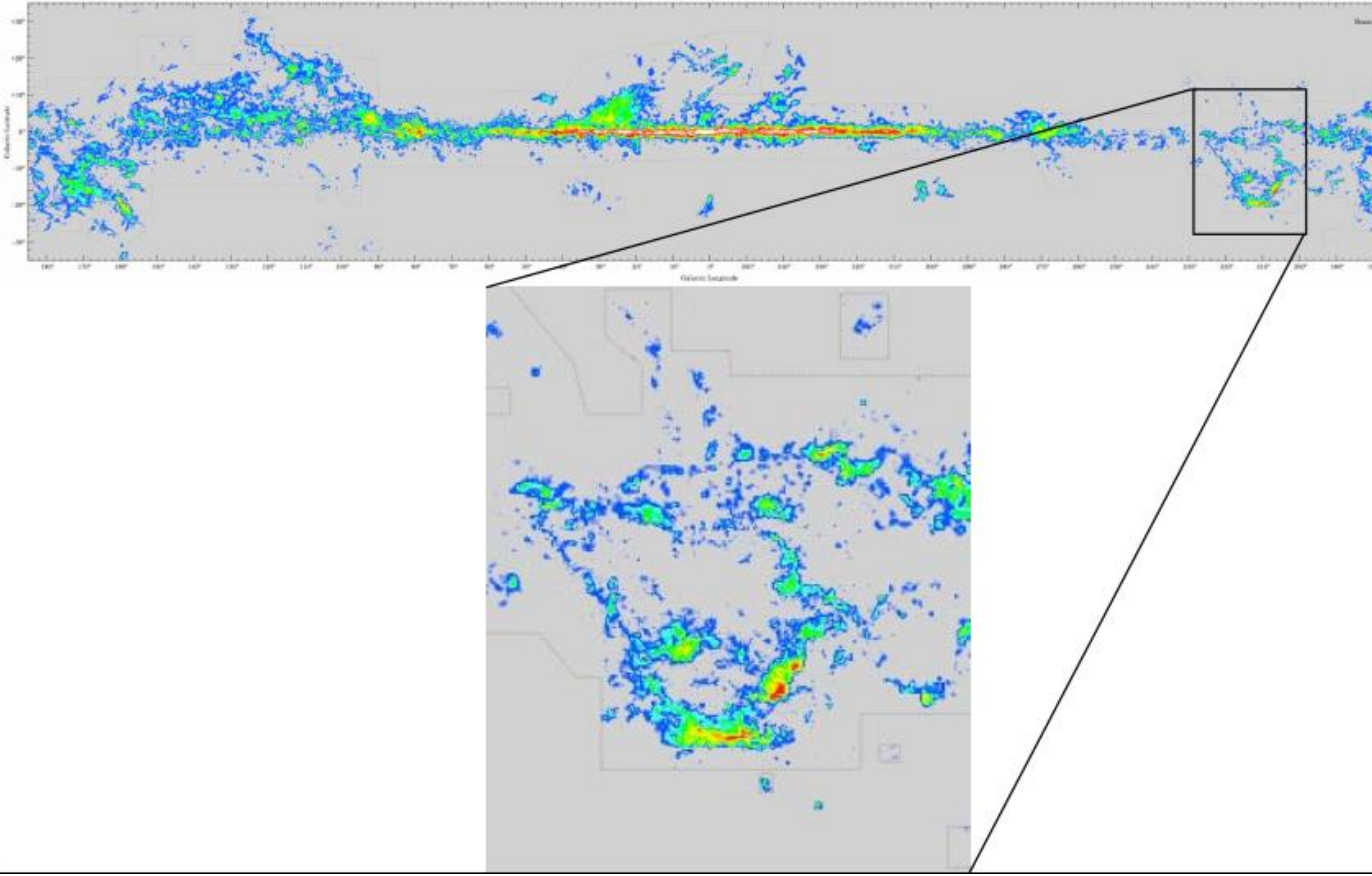


Dame et al. 2001

Primer oblaka Orion A i B

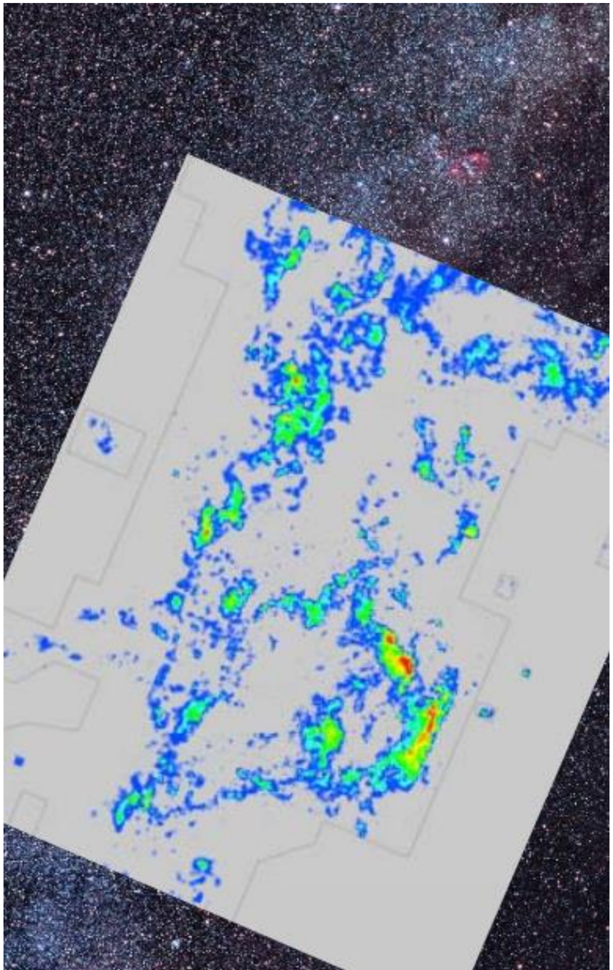


Blitz & Williams 1999



Dame et al. 2001

Simnci u vidljivom i mape CO



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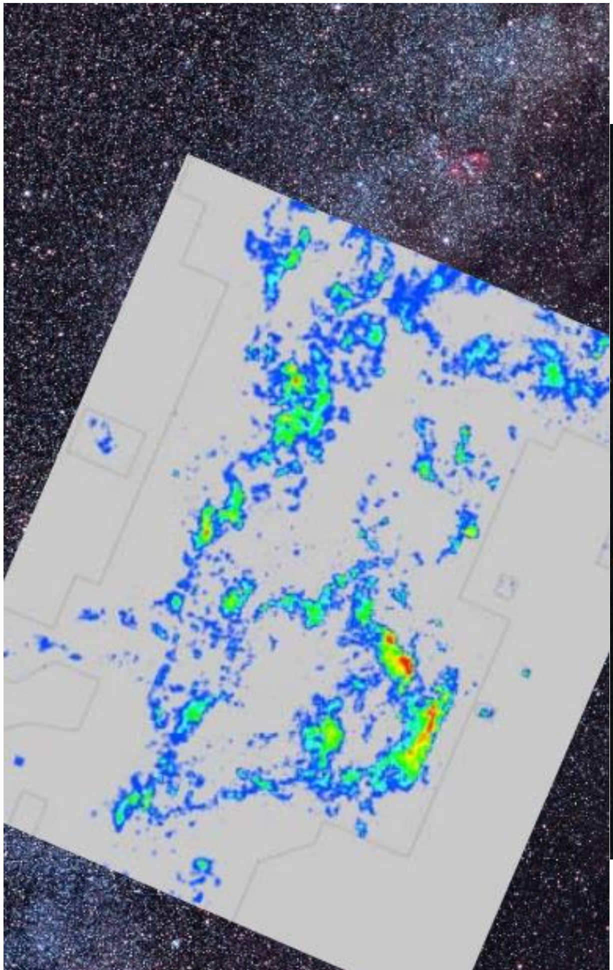
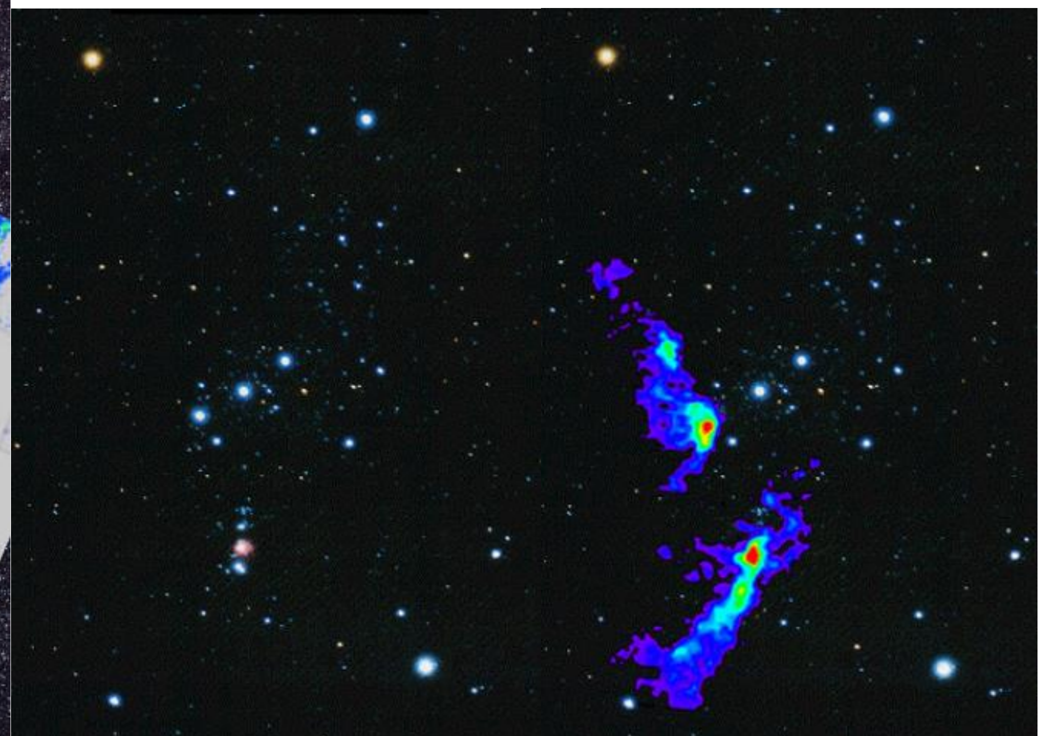
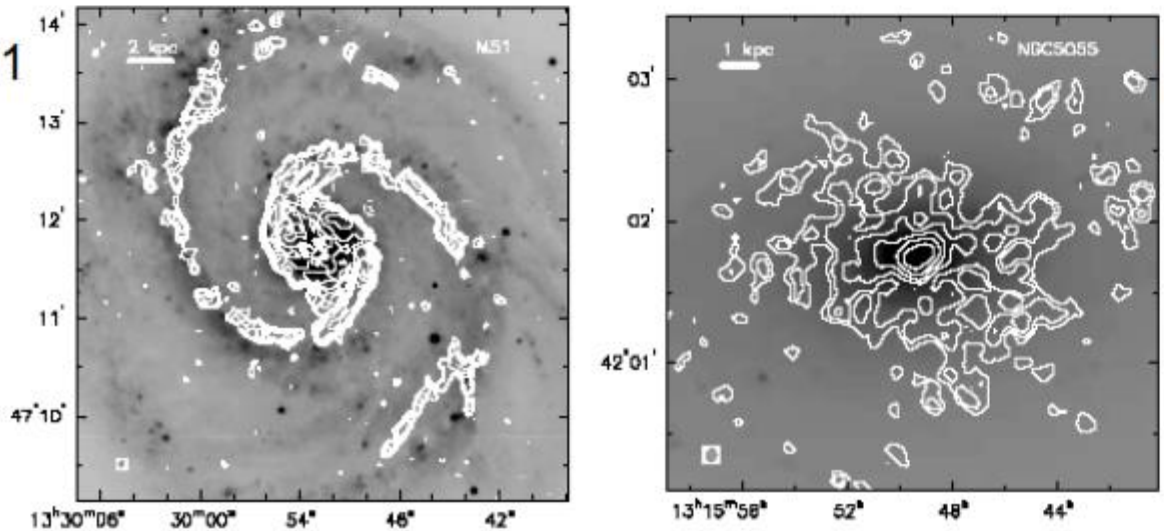




CO mape drugih galaksija

M 51



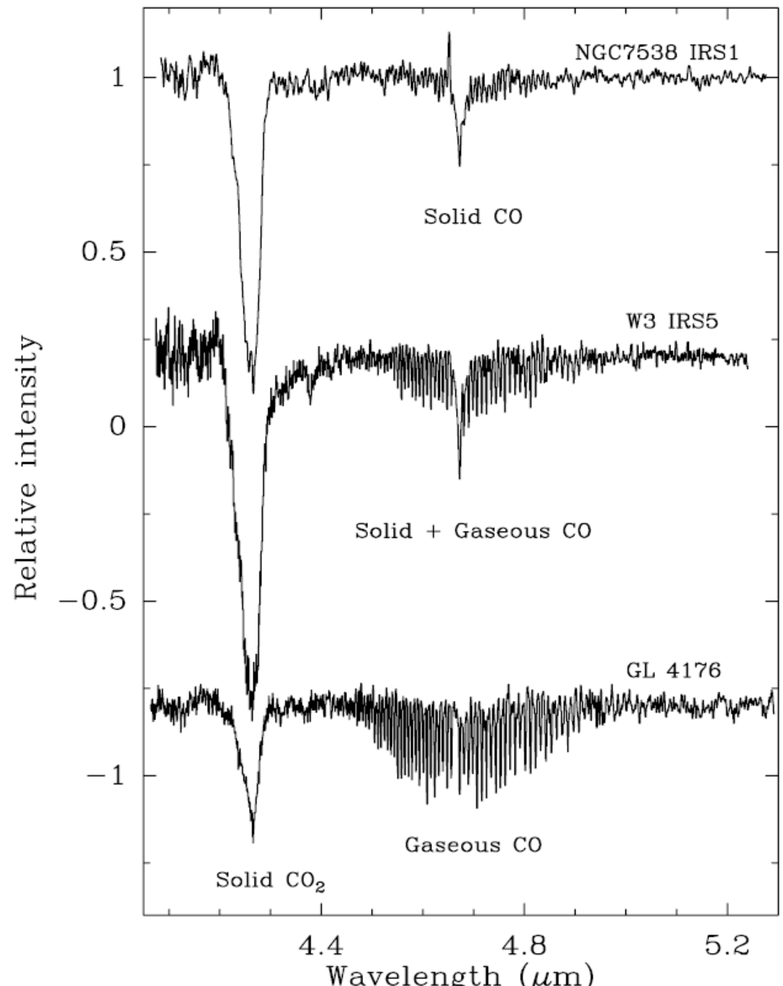
NGC 5055

Figure 1. *Left*: CO in M51 from the BIMA Survey of Nearby Galaxies (SONG), overlaid on an optical image of the galaxy. The image contains zero spacing data and thus samples all of the spatial frequencies to the resolution limit (shown by the small box in the lower left). The CO is very strongly concentrated to the spiral arms and lies upstream of most of the ionized gas. *Right*: BIMA SONG image of the CO in NGC 5055 overlaid on an optical image showing that the galaxy is devoid of large-scale spiral structure at visible wavelengths. Some of the off-nuclear CO peaks are associated with weak spiral arms seen in the near infrared. The difference in CO morphology between these two galaxies is rather striking.

Blitz & Williams 1999

Primer spektra CO

- Apsorpcija na spektrima mladih zvezda
  - posmatranja ka tri zvezde
  - spektar različitih agregatnih stanja



van Dishoeck et al. 1999

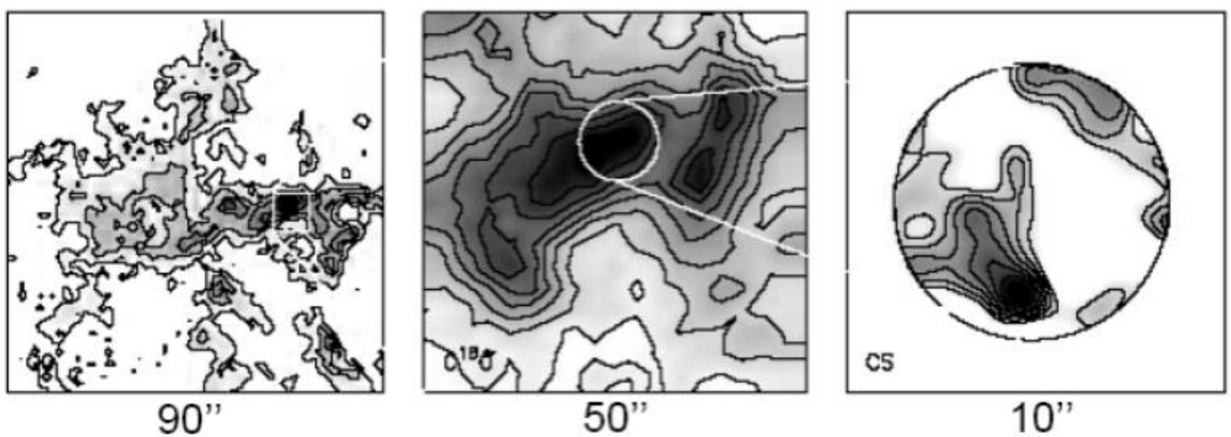
Spisak molekula detektovanih do 2003

2 atoms	**3 atoms**	**4 atoms**	**5 atoms**	**6 atoms**	**7 atoms**	**8 atoms**	**$\geq$9 atoms**
Hydrogen family							
H_2	H_3^+						
Carbon family							
C_2	**C_3**	c-C_3H	C_5	C_5H	C_6H	C_7H	C_8H
CH	C_2H	l-C_3H	C_4H	l-C_4H_2	CH_3C_2H	C_6H_2	CH_3C_4H
CH^+	CH_2	**C_2H_2**	l-C_3H_2	C_2H_4		(C_2H_6)	*c-C_6H_6*
		CH_2D^+?	c-C_3H_2				
			CH_4				
Oxygen + hydrogen and/or carbon							
CO	C_2O	C_3O	**$HCOOH$**	**CH_3OH**	$HCOCH_3$	**$HCOOCH_3$**	$(CH_3)_2O$
CO^+	HCO	$HOCO^+$	H_2C_2O	HC_2CHO	c-C_2H_4O	CH_3COOH	CH_3CH_2OH
OH	**HCO^+**	**H_2CO**	H_2COH^+			CH_2OHCHO	$(CH_3)_2CO$
	HOC^+	**H_3O^+**			CH_2CHOH		
	H_2O						
	(H_2O^+)						
	CO_2						
Nitrogen + hydrogen and/or carbon							
CN	**HCN**	C_3N	**HC_3N**	**CH_3CN**	HC_5N	CH_3C_3N	HC_7N
NH	**HNC**	$HCCN$	CH_2CN	CH_3NC	CH_2CHCN		HC_9N
	N_2H^+	$HCNH^+$	HC_2NC	HC_3NH^+	NH_2CH_3		$HC_{11}N$
	NH_2	H_2CN	H_2CHN	C_5N			CH_3CH_2CN
		NH_3	H_2NCN				CH_3C_5N?
			HNC_3				

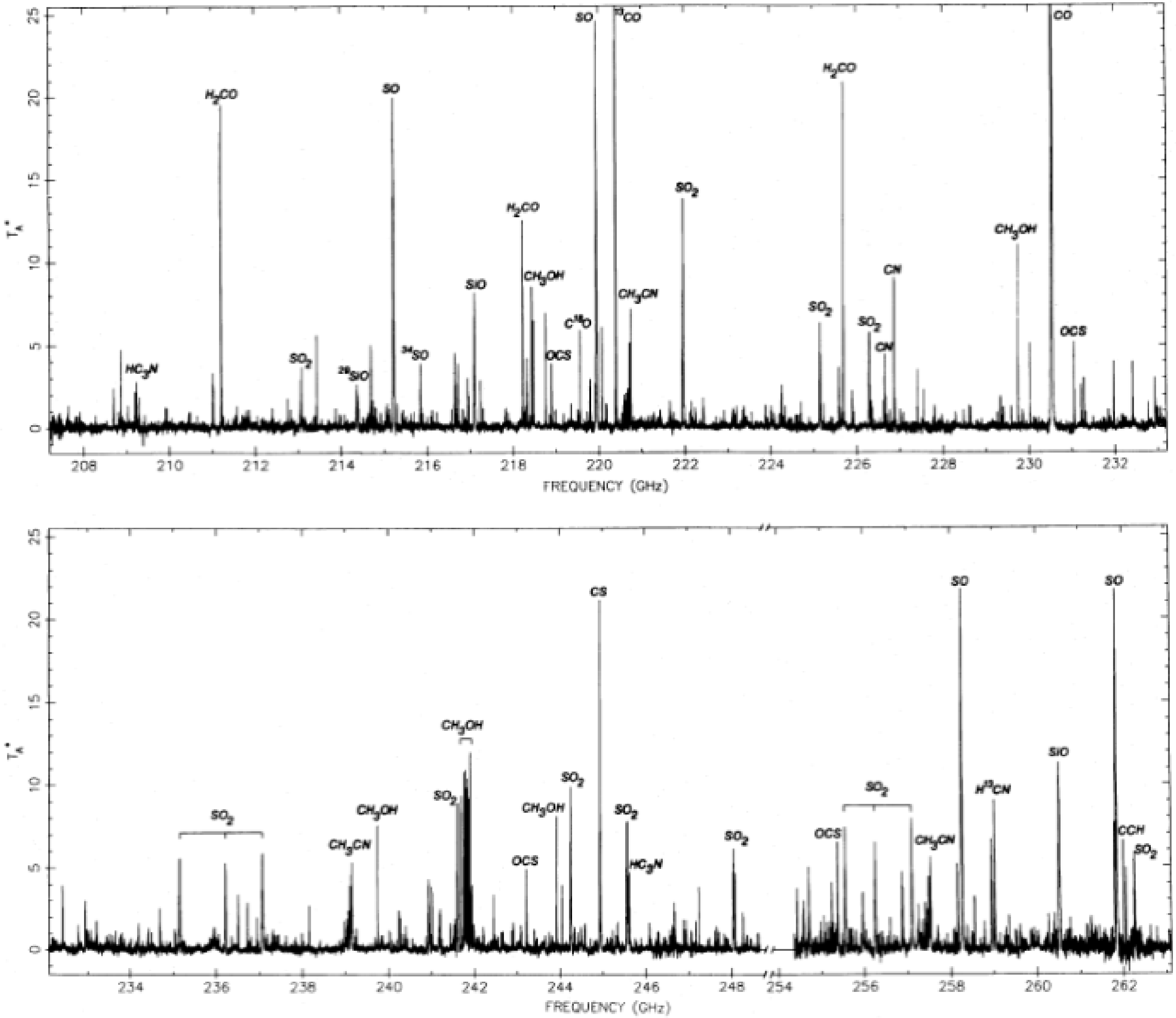
2 atoms	**3 atoms**	**4 atoms**	**5 atoms**	**6 atoms**	**7 atoms**	**8 atoms**	**≥9 atoms**
Nitrogen + oxygen + hydrogen and/or carbon							
NO	HNO	HNCO		NH_2CHO			NH_2CH_2COOH?
	N_2O						
Molecules with sulphur							
CS	C_2S	C_3S		CH_3SH			
SO	HCS^+	HNCS					
SO^+	H_2S	**H_2CS**					
NS	**OCS**						
	SO_2						
Miscellaneous molecules							
SiO	SiCN	*SiC_3*	*SiC_4*				
SiS	*c-SiC_2*		*SiH_4*				
HF	*MgCN*						
SiC	*MgNC*						
CP	*NaCN*						
HCl	*AlNC*						
KCl							
NaCl							
PN							
SiN							
AlF							
AlCl							
SH							
FeO?							

Struktura MC

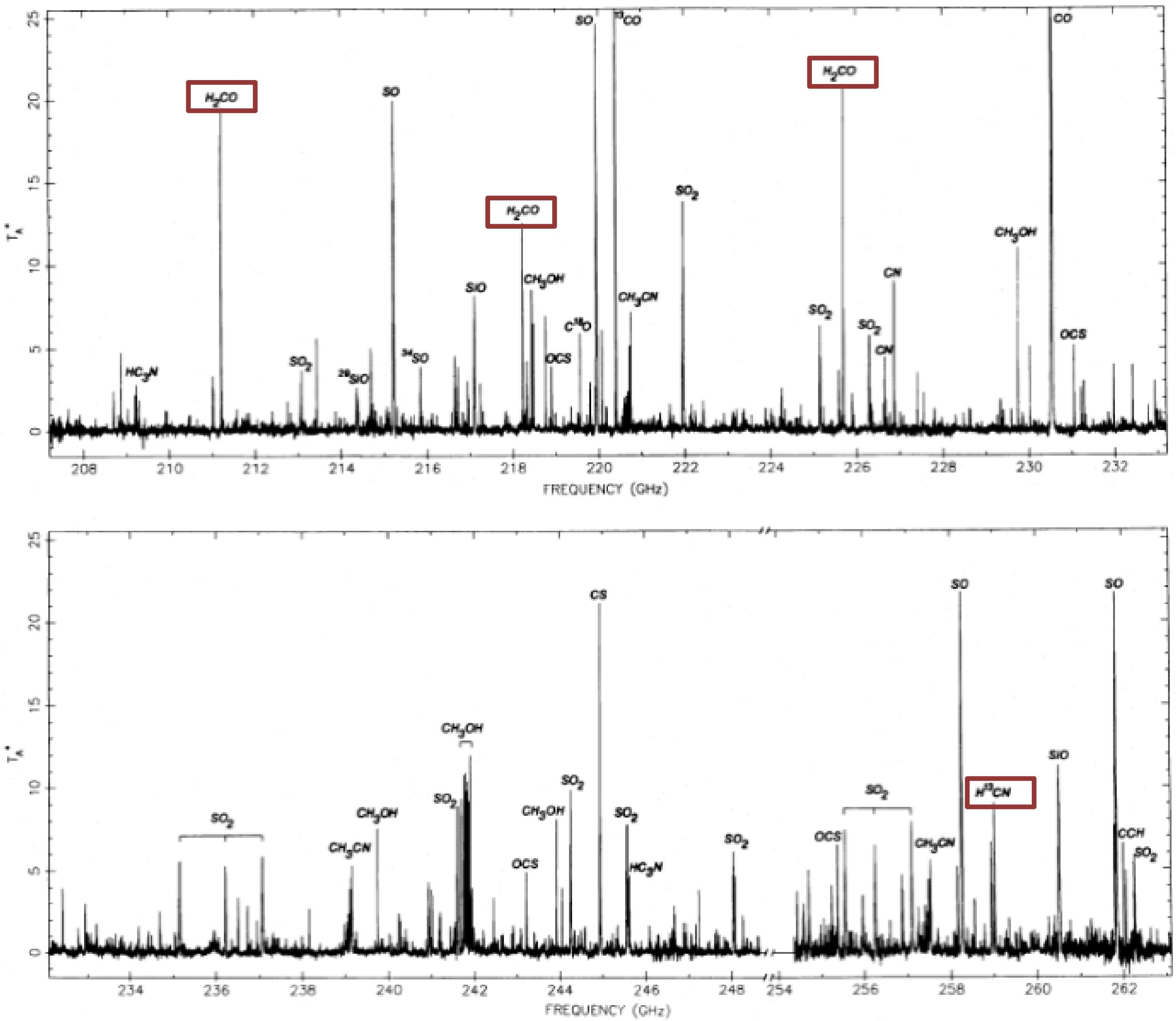
- Gusto jezgro
- Zbijene strukture
- Centralni oblak molekula
- Fotodisocijativni regioni



Blitz & Williams 1999



Genzel & Stutzki 1989



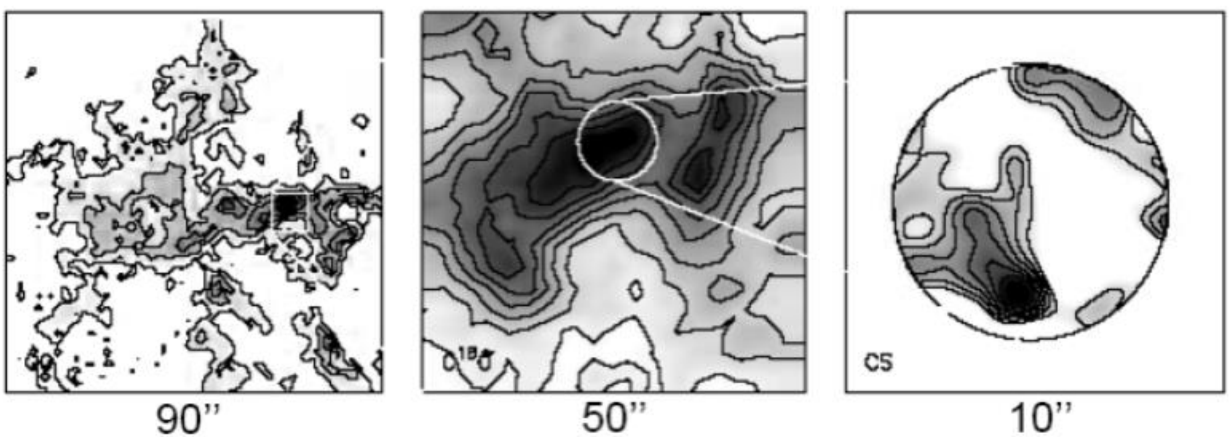
Genzel & Stutzki 1989

Markeri gustog gasa

Molecule	Transition	Frequency (GHz)	E/k (K)	n_{crit} (cm^{-3}) @ 10 K	n_{eff} (cm^{-3}) @ 10 K
CS	1-0	49.0	2.4	4.6×10^4	7.0×10^3
	2-1	98.0	7.1	3.0×10^5	1.8×10^4
	3-2	147.0	14	1.3×10^6	7.0×10^4
HCO^+	1-0	89.2	4.3	1.7×10^5	2.4×10^3
	3-2	267.6	26	4.2×10^6	6.3×10^4
HCN	1-0	88.6	4.3	2.6×10^6	2.9×10^4
	3-2	265.9	26	7.8×10^7	7.0×10^5
H_2CO	2_{12}-1_{11}	140.8	6.8	1.1×10^6	6.0×10^4
	3_{13}-2_{12}	211.2	17	5.6×10^6	3.2×10^5
	4_{14}-3_{13}	281.5	30	9.7×10^6	2.2×10^6
NH_3	(1,1)	23.7	1.1	1.8×10^3	1.2×10^3
	(2,2)	23.7	42	2.1×10^3	3.6×10^4

Struktura MC

- Gusto jezgro
- Zbijene strukture
- Centralni oblak molekula
- Fotodisocijativni regioni



Blitz & Williams 1999

Rotacioni prelazi

- Izraz za energiju: $E_{rot} = \frac{1}{2I}(\text{angular momentum})^2$

$$(\text{angular momentum})^2 = J(J+1)\left(\frac{h}{2\pi}\right)^2 \quad J = 0, 1, 2, 3 \ldots \quad \Delta J = +1 \text{ or } -1$$

  - u slučaju linearnog molekula $I = \mu r^2$
  - možemo to zapisati na sledeći način:

$$E_{rot} = J(J+1)\left(\frac{h}{2\pi}\right)^2 \frac{1}{2I} + B = h/(8\pi^2 I) \longrightarrow E_{rot}(J) = hBJ(J+1)$$

  - ovakav prelazak (u slučaju krutog rotatora) stvara emisiju ili apsorpciju na frekvenciji:

$$\nu = \Delta E/h = B[(J''+1)(J''+2) - J''(J''+1)] = 2B(J''+1)$$

Vibracioni nivoi

- Za odstupanje $r - r_e$ važi: $F = -k(r - r_e)$;

  (u klasičnoj mehanici) $V = (1/2)k(r - r_e)^2$.

- U kvantnoj mehanici: $E_{vib}(v) = h\nu_{osc}(v + 1/2)$ $\nu_{osc} = 1/(2\pi)\sqrt{(k/\mu)}$,

  $v = 0, 1, 2, 3...$

  - za velike vrednosti *v* molekuli provode većinu vremena daleko od ravnotežnog položaja
  - privilegovano širenje molekula
  - promena u vrednosti *B*, odnosno *I*
    - » *centrifugalna sila*

      $\mu\omega^2 r = \mu \text{ (angular momentum}/I)^2 r = J(J+1)h^2/(4\pi^2)1/(\mu r^3)$

    - » *ravnoteža?*

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- Usled promena r → promena $I = \mu r^2$
  - izraženo za velika v, J (za hladne molekule nije bitno)

$$k(r - r_e) = \frac{J(J+1)\left(\frac{h}{2\pi}\right)^2}{\mu r^3}$$

$$= \frac{J(J+1)\left(\frac{h}{2\pi}\right)^2}{\mu r_e^3\left(1 + \frac{r - r_e}{r_e}\right)^3}$$

$$\text{total energy} = \frac{J(J+1)\left(\frac{h}{2\pi}\right)^2}{2\mu r^2} - \tfrac{1}{2}k(r - r_e)^2$$

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$$\simeq hBJ(J+1) - \frac{J^2(J+1)^2h^4}{32\pi^4\mu^2 r_e^6 k}$$

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$(r - r_e)/r_e \ll 1$

$$k(r - r_e) = \frac{J(J+1)\left(\frac{h}{2\pi}\right)^2}{\mu r^3}$$

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- Usled promena r → promena $I = \mu r^2$
  - izraženo za velika v, J (za hladne molekule nije bitno) $(r - r_e)/r_e \ll 1$

$$\text{total energy} = \frac{J(J+1)\left(\frac{h}{2\pi}\right)^2}{2\mu r^2} + \frac{1}{2}k(r - r_e)^2$$

$$= \frac{J(J+1)\left(\frac{h}{2\pi}\right)^2}{2\mu r_e^2\left(1 + \frac{r - r_e}{r_e}\right)^2} + \frac{1}{2}k(r - r_e)^2$$

$$\simeq hBJ(J+1) - \frac{J^2(J+1)^2h^4}{32\pi^4\mu^2 r_e^6 k}$$

$$E = hBJ(J+1) - hDJ^2(J+1)^2 + \cdots$$

$$D = 16\pi^2 B^3\mu/k = 4B^3/\nu_{osc}^2$$

$$\nu = 2B(J'' + 1) - 4D(J'' + 1)^3$$

$$B_v = B_e - \alpha(v + 1/2) + \cdots \qquad D_v = D_e - \beta(v + 1/2)$$

Verovatnoća?

- verovatnoća prelaza je data sa: $A_{ji} = \frac{64\pi^4}{3hc^3 4\pi\varepsilon_0} \nu^3 |d|^2$
  - dipolni momenat: $d = e \int \Phi_j r \Phi_i \, \mathrm{d}V$

$$d^2 = f(J)(e \int \phi_i r \phi_i \mathrm{d}V)^2 = \frac{(J+1)}{(2J+3)} d_p^2$$

  - verovatnoća: $A_{ji} = 1.046 * 10^{21} \nu^3 d_p^2 \frac{(J+1)}{(2J+3)}$
  - particiona funkcija:

$$U = \sum_j (2J+1) \exp\left[-\frac{hBJ(J+1)}{kT_{ex}} \right] \simeq \int_0^\infty (2J+1) \exp\left[-\frac{hBJ(J+1)}{kT_{ex}} \right] \mathrm{d}J$$

$$\simeq \int_0^\infty \exp\left[-\frac{hBJ'}{kT_{ex}} \right] \mathrm{d}J', \quad \text{with } J' = J^2 + J$$

$$\simeq \frac{kT_{ex}}{hB}$$

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  - particiona funkcija: $U = (kT_{ex})/(hB) + 1/3$

$$U = \sum_j (2J+1)\exp\left[-\frac{hBJ(J+1)}{kT_{ex}}\right] \simeq \int_0^\infty (2J+1)\exp\left[-\frac{hBJ(J+1)}{kT_{ex}}\right] \mathrm{d}J$$

$$\simeq \int_0^\infty \exp\left[-\frac{hBJ'}{kT_{ex}}\right] \mathrm{d}J', \quad \text{with } J' = J^2 + J$$

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Verovatnoća?

- verovatnoća prelaza je data sa: $A_{ji} = \frac{64\pi^4}{3hc^3 4\pi\varepsilon_0} \nu^3 |d|^2$

CO u osnovnom stanju
nema nuklearni spin
a ugaoni momenat = 0

veoma jednostavan slučaj

$$\simeq \int_0^\infty \exp\left[-\frac{hBJ'}{kT_{ex}}\right] dJ', \quad \text{with } J' = J^2 + J$$

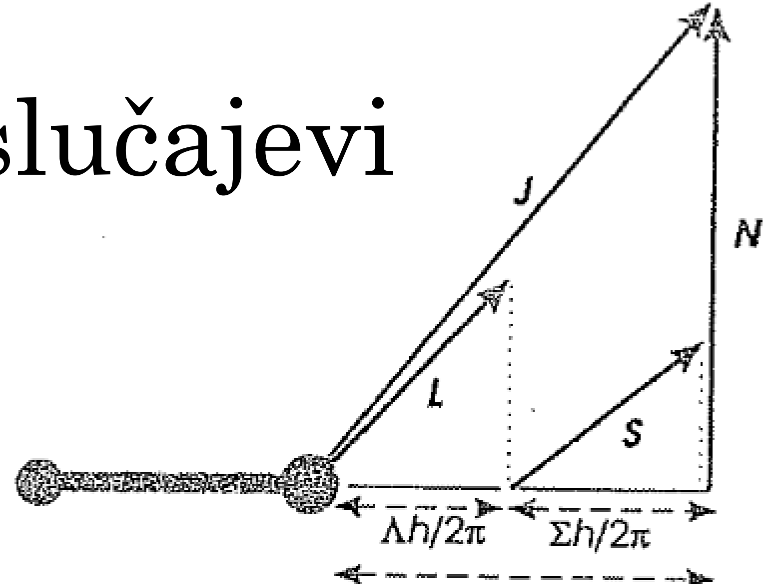
$$\simeq \frac{kT_{ex}}{hB}$$

Šta utiče na energiju i intenzitet rotacionih i vibracionih linija?

dužina molekula, svedena masa
dipolni momenat, ose simetrije
superpozicija kvantnih stanja,
prostorna orijentacija molekula...

Hundovi slučajevi

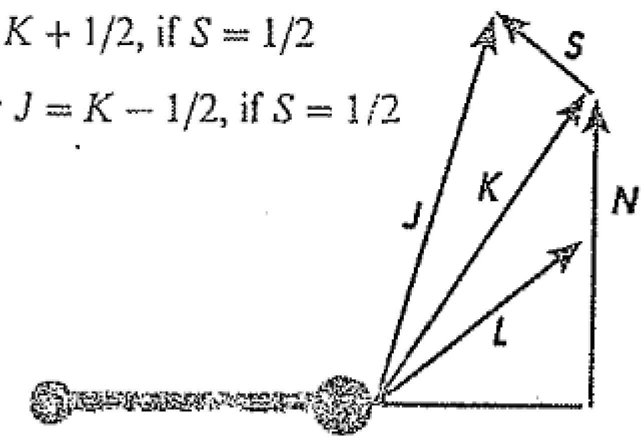
- Linearan molekul
- Slaganje spinova



(a)

$$\text{energy} = hBK(K+1) + \text{constant} * K \quad \text{for } J = K + 1/2, \text{ if } S = 1/2$$

$$\text{energy} = hBK(K+1) - \text{constant} * (K+1) \quad \text{for } J = K - 1/2, \text{ if } S = 1/2$$



(b)

Ne-linearni molekuli

- Uopšten slučaj

$$E = \tfrac{1}{2}I_x\omega_x^2 + \tfrac{1}{2}I_y\omega_y^2 + \tfrac{1}{2}I_z\omega_z^2 = \frac{(\text{angular Momentum about } x)^2}{2I_x} + \frac{(\text{angular Momentum about } y)^2}{2I_y} + \frac{(\text{angular Momentum about } z)^2}{2I_z}$$

- U sistemu gde je jedna od osa odabrana za osu molekula: $E = hBJ(J+1) + h(A-B)\Omega^2$

$A = h/(8\pi^2 I_z)$

$$(\text{angular momentum about } x)^2 + (\text{angular momentum about } y)^2 = N^2 = J^2 - \Omega^2 = (J(J+1) - \Omega^2)\,[h/(2\pi)]^2$$

- Kvadripolni član takođe utiče na linije
  - za izražen magnetni momenat

Šta utiče na energiju i intenzitet rotacionih i vibracionih linija?

dužina molekula, svedena masa
dipolni momenat, ose simetrije
superpozicija kvantnih stanja,
prostorna orijentacija molekula...

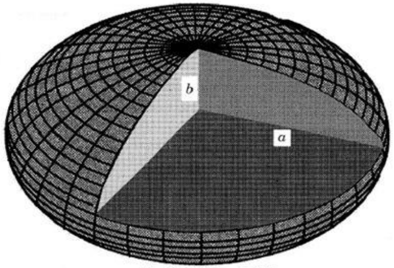
Oblik molekula

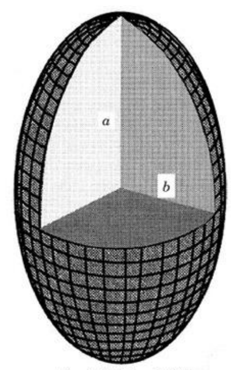
- Momenti inercija duž glavnih osa su obeleženi u skladu sa konvencijom:

$$I_c \geqslant I_b \geqslant I_a;$$

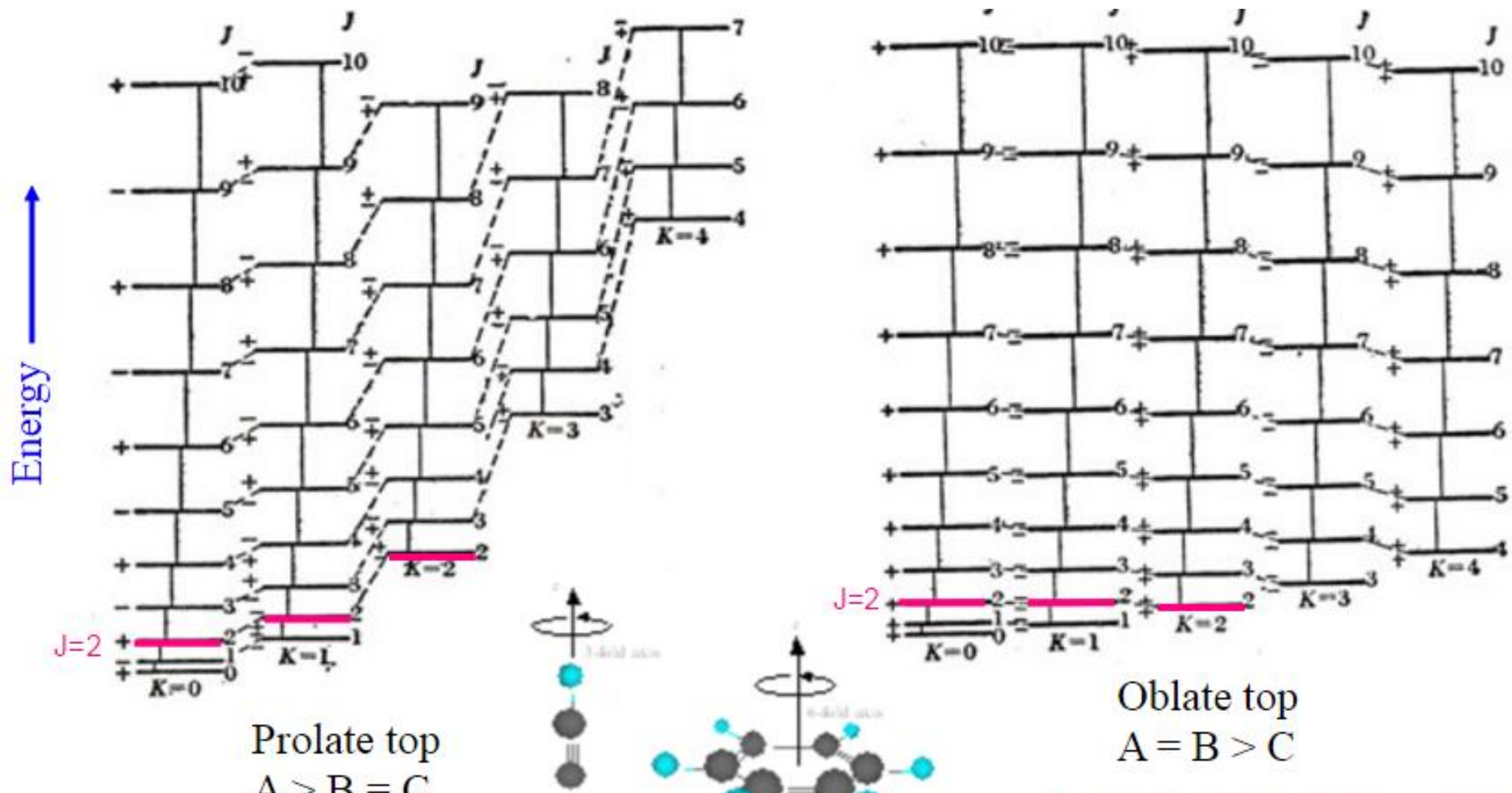
- Simetrični
  - elektronski prelasci dozvoljeni
  - rotacioni i vibracioni nisu
- Sferno simetrični
- Kružno simetrični (Symetric Top)
  - Oblate (a) $I_c > I_b = I_a$
  - Prolate (b) $I_c = I_b > I_a;$
- Asimetrični

NH_3.





Spektar Prolate/Oblate molekula



G. Herzberg, Molecular Spectra and Molecular Structure II. Infrared and Raman Spectra of Polyatomic Molecules, Van Nostrand Reinhold (1945), p. 25.

Oblate: benzene, C_6H_6, ammonia, NH_3

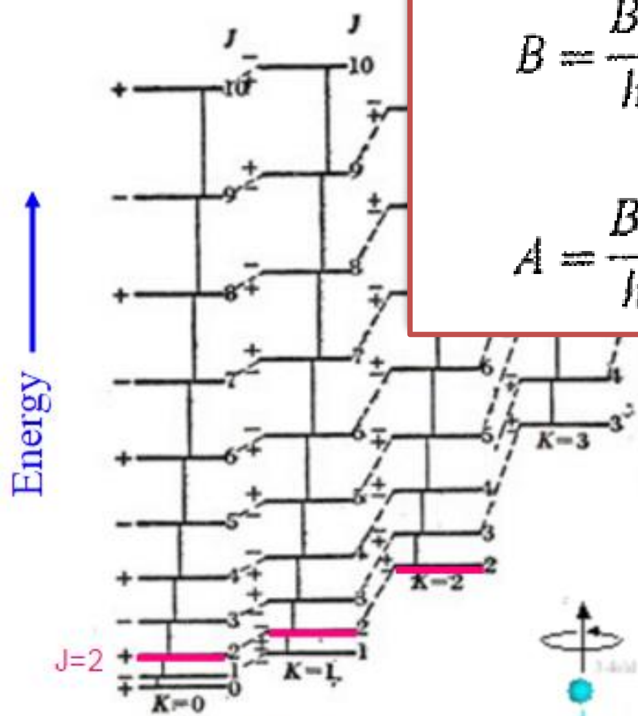
Prolate: chloromethane, CH_3Cl, propyne, $CH_3C{\equiv}CH$

$$E(J,K) = hBJ(J+1) + h(A-B)K^2$$

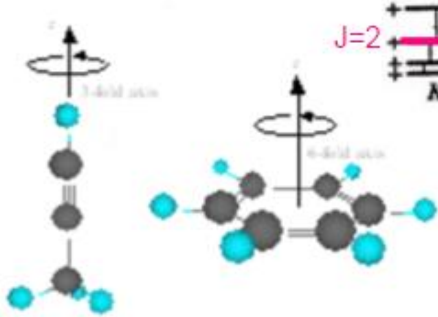
$$B = \frac{B'_b}{h}\left(\frac{h}{2\pi}\right) = \frac{h}{8\pi^2 I_b}$$

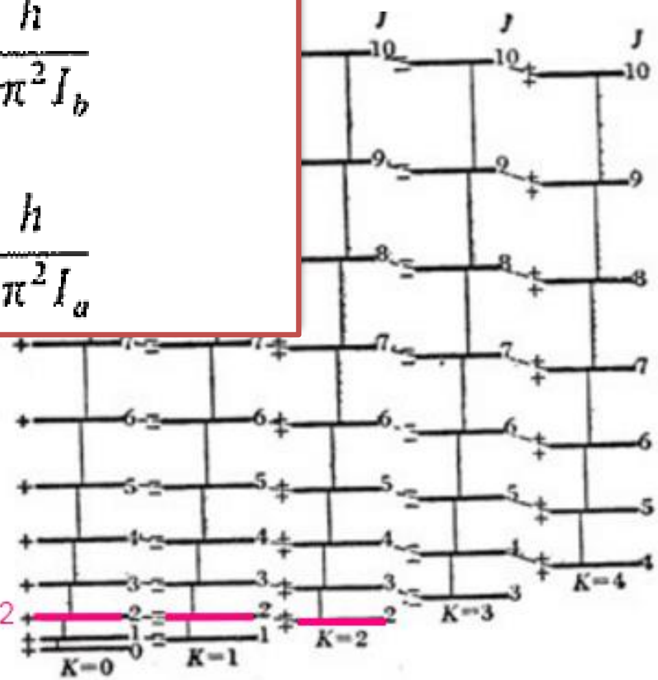
$$A = \frac{B'_a}{h}\left(\frac{h}{2\pi}\right) = \frac{h}{8\pi^2 I_a}$$

Spektar ... olekula



Prolate top
A > B = C





Oblate top
A = B > C

G. Herzberg, Molecular Spectra and Molecular Structure II. Infrared and Raman Spectra of Polyatomic Molecules, Van Nostrand Reinhold (1945), p. 25.

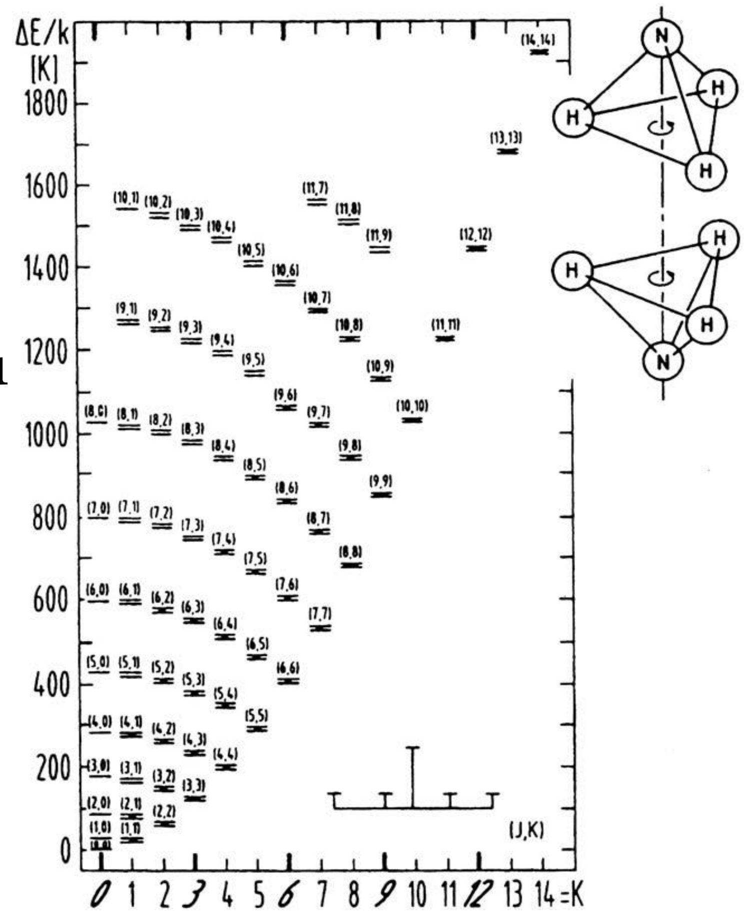
Oblate: benzene, C_6H_6, ammonia, NH_3

Prolate: chloromethane, CH_3Cl, propyne, $CH_3C{\equiv}CH$

Orto i Para forme

- Orto – paralelni nuk. spin
- Para – anti-paralelan spin

- Prelazak iz jedne u drugu formu je izričito zabranjen prelaz
  - detekcija H_2
  - temperatura formiranja molekula



Jačina linija molekula – primer na CO

- Kako odrediti
    - Temperaturu?
    - Linijsku gustinu?
  - CO ima više prelaza i može biti sačinjen od više izotopa
    - niz linija
      - raspodela po energetskim nivoima
      - potvrđuju/opovrgavaju LTE
      - daju uvid u T sredine
      - optički guste/tanke
    - niz frekvencija u radio, IC itd.
      - CMB ili drugi pozadinski izvor

Temperatura sjaja

$$\int T_B \, d\nu = \frac{c^2 h}{8\pi k} \frac{A_{ji} g_j}{g_i} \frac{1}{\nu} \frac{g_i}{U} \exp\left[-\frac{E}{kT_{ex}} \right] (N_{TOT} \rho R)$$

$$= \frac{c^2 h}{8\pi k} \frac{A_{ji}(2J+3)}{(2J+1)} \frac{1}{2B(J+1)} \frac{hB}{kT_{ex}} (2J+1) \exp\left[-\frac{hBJ(J+1)}{kT_{ex}} \right] (N_{TOT} \rho R)$$

$$= \frac{c^2 h^2}{16\pi k^2} \frac{1}{T_{ex}} A_{ji} \frac{(2J+3)}{(J+1)} \exp\left[-\frac{hBJ(J+1)}{kT_{ex}} \right] (N_{TOT} \rho R)$$

Temperatura sjaja

$$\int T_{\mathrm{B}}\,\mathrm{d}\nu = \frac{c^2 h}{8\pi k}\frac{A_{ji} g_j}{g_i}\frac{1}{\nu}\frac{g_i}{U}\exp\left[-\frac{E}{kT_{\mathrm{ex}}}\right](N_{\mathrm{TOT}}\rho R)$$

$$= \frac{c^2 h}{8\pi k}\frac{A_{ji}(2J+3)}{(2J+1)}\frac{1}{2B(J+1)}\frac{hB}{kT_{\mathrm{ex}}}(2J+1)\exp\left[-\frac{hBJ(J+1)}{kT_{\mathrm{ex}}}\right](N_{\mathrm{TOT}}\rho R)$$

$$= \frac{c^2 h^2}{16\pi k^2}\frac{1}{T_{\mathrm{ex}}}\underline{A_{ji}}\frac{(2J+3)}{(J+1)}\exp\left[-\frac{hBJ(J+1)}{kT_{\mathrm{ex}}}\right](N_{\mathrm{TOT}}\rho R)$$

$$\int T_{\mathrm{B}}\,\mathrm{d}\nu = \frac{4\pi^3 h}{3ck^2(4\pi\varepsilon_0)}\frac{\nu^3}{T_{\mathrm{ex}}}d_p^2\exp\left[-\frac{hBJ(J+1)}{kT_{\mathrm{ex}}}\right](N_{\mathrm{TOT}}\rho R)$$

$$= \frac{32\pi^3 h}{3ck^2(4\pi\varepsilon_0)}\frac{B^3(J+1)^3}{T_{\mathrm{ex}}}d_p^2\exp\left[-\frac{hBJ(J+1)}{kT_{\mathrm{ex}}}\right](N_{\mathrm{TOT}}\rho R)$$

Temperatura sjaja

$$\int T_{\mathrm{B}}\,\mathrm{d}\nu = \frac{c^2 h}{8\pi k}\frac{A_{ji} g_j}{g_i}\frac{1}{\nu}\frac{g_i}{U}\exp\left[-\frac{E}{kT_{\mathrm{ex}}}\right](N_{\mathrm{TOT}}\rho R)$$

$$= \frac{c^2 h}{8\pi k}\frac{A_{ji}(2J+3)}{(2J+1)}\frac{1}{2B(J+1)}\frac{hB}{kT_{\mathrm{ex}}}(2J+1)\exp\left[-\frac{hBJ(J+1)}{kT_{\mathrm{ex}}}\right](N_{\mathrm{TOT}}\rho R)$$

$$= \frac{c^2 h^2}{16\pi k^2}\frac{1}{T_{\mathrm{ex}}}\underline{A_{ji}}\frac{(2J+3)}{(J+1)}\exp\left[-\frac{hBJ(J+1)}{kT_{\mathrm{ex}}}\right](N_{\mathrm{TOT}}\rho R)$$

Koliko je optički gusta sredina?

$$\int T_{\mathrm{B}}\,\mathrm{d}\nu = \frac{4\pi^3 h}{3ck^2(4\pi\varepsilon_0)}\frac{\nu^3}{T_{\mathrm{ex}}}d_p^2\exp\left[-\frac{hBJ(J+1)}{kT_{\mathrm{ex}}}\right](N_{\mathrm{TOT}}\rho R)$$

$$= \frac{32\pi^3 h}{3ck^2(4\pi\varepsilon_0)}\frac{B^3(J+1)^3}{T_{\mathrm{ex}}}d_p^2\exp\left[-\frac{hBJ(J+1)}{kT_{\mathrm{ex}}}\right](N_{\mathrm{TOT}}\rho R)$$

Linije različitih izotopa

- Odnos između nekoliko izotopa C

$$N(^{12}CO) \simeq 76\ N(^{13}CO)$$

$$N(^{12}CO) = 560\ N(C^{18}O)$$

- Za dugo-talasnu aprox. ove linije imaju istu:
  - temperaturu pozadinskog zračenja $T_B = T_{ex}(1 - e^{-\tau})$
  - temperaturu ekscitacije T_{ex}
- Stoga važi: $\frac{T_B(^{12}C^{16}O)}{T_B(^{13}C^{16}O)} = \frac{(1 - e^{-\tau(^{12}C^{16}O)})}{(1 - e^{-\tau(^{13}C^{16}O)})}$

$N(^{12}C)/N(^{13}C) = R,$

$\tau(^{12}C^{16}O) = R\tau(^{13}C^{16}O)$

optički tanak sl.

$\tau = T_B/T_{ex}$

$T_B(^{13}C^{16}O)/\ T_B(^{12}C^{18}O) = N(^{13}C)/N(^{12}C) \cdot N(^{16}O)/N(^{18}O)$

$$\int \tau_v \, dV = \frac{8\pi^3 B d_p^2}{3k4\pi\varepsilon_0} \frac{N_{TOT}\rho R(J+1)e^{-hBJ(J+1)/kT_{ex}}}{T_{ex} + \frac{hB}{3k}} (1 - e^{-h\nu/kT_{ex}})$$

Linije različitih izotopa

- Odnos između nekoliko izotopa C

$$N(^{12}CO) \simeq 76\ N(^{13}CO)$$
$$N(^{12}CO) = 560\ N(C^{18}O)$$

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  - temperaturu ekscitacije T_{ex}
- Stoga važi: $\dfrac{T_B(^{12}C^{16}O)}{T_B(^{13}C^{16}O)} = \dfrac{(1 - e^{-\tau(^{12}C^{16}O)})}{(1 - e^{-\tau(^{13}C^{16}O)})}$

$$N(^{12}C)/N(^{13}C) = R,$$

$$\tau(^{12}C^{16}O) = R\tau(^{13}C^{16}O)$$

optički tanak sl.

$$\tau = T_B/T_{ex}$$

$$N_{TOT}\,\rho R(^{12}C^{16}O) = 2.39 \times 10^{15}\,\frac{e^{hB_{12}J(J+1)/kT_{ex}}}{J+1}\,\frac{T_{ex} + 0.93}{1 - e^{-h\nu_{12}/kT_{ex}}}\int \tau\, dV\, m^{-2}$$

$$N_{TOT}\,\rho R(^{13}C^{16}O) = 2.49 \times 10^{15}\,\frac{e^{hB_{13}J(J+1)/kT_{ex}}}{J+1}\,\frac{T_{ex} + 0.89}{1 - e^{-h\nu_{13}/kT_{ex}}}\int \tau\, dV\, m^{-2}$$

Prelazi na različit nivo

- Unutar istog molekula od istih izotopa posmatramo prelaske na (niži) nivo *l*, *m*

$$\frac{\tau_\nu(m \text{ to } m+1)}{\tau_\nu(l \text{ to } l+1)} = \frac{(J_m+1)}{(J_l+1)} \frac{e^{-E_m/kT_{ex}}}{e^{-E_l/kT_{ex}}} \frac{1-e^{-h\nu_m/kT_{ex}}}{1-e^{-h\nu_l/kT_{ex}}}$$

- Ukoliko su nivoi uzastopni ($m=l+1$)

$$\frac{\tau_\nu(l+1 \text{ to } l+2)}{\tau_\nu(l \text{ to } l+1)} = \frac{J_l+2}{J_l+1} \frac{1-e^{-h\nu_m/kT_{ex}}}{e^{h\nu_l/kT_{ex}}-1}$$

Detaljnije – sa pozadinskim zračenjem

$$T'_B = c^2/(2k\nu^2) I_\nu.$$

- Prisutnost pozadinskog zračenja (T=2.7K)

$$T_B = T_{ex}(1 - e^{-\tau}) + T_{BCK} e^{-\tau} \quad \text{or} \quad T_{OBS} = T_B - T_{BCK} = (T_{ex} - T_{BCK})(1 - e^{-\tau})$$

- Ukoliko predstavimo preko Planka

$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT_{BCK}} - 1} e^{-\tau_\nu} + \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT_{ex}} - 1} (1 - e^{-\tau_\nu})$$

$$T'_{OBS} = T'_B - T'_{BCK} = \frac{h\nu}{k}\left[\frac{1}{e^{h\nu/kT_{ex}} - 1} - \frac{1}{e^{h\nu/kT_{BCK}} - 1}\right](1 - e^{-\tau_\nu})$$

$$T'_{OBS}(1\text{–}0) = 5.532\left(\frac{1}{[e^{5.532/T_{ex}} - 1]} - 0.1479\right)(1 - e^{-\tau_\nu}) \quad \text{for } ^{12}C^{16}O$$

$$= 5.289\left(\frac{1}{[e^{5.289/T_{ex}} - 1]} - 0.1642\right)(1 - e^{-\tau_\nu}) \quad \text{for } ^{13}C^{16}O$$

Rezultat razmatranja

- Ako uzmemo da je temperatura ekscitacije nekoliko puta veća od pozadinske dobijamo:

$$N_{\mathrm{TOT}}\rho R = 4.3 \times 10^{14} \frac{(T_{\mathrm{ex}} + 0.93)}{\mathrm{e}^{-5.53/T_{\mathrm{ex}}}} \int \frac{T'_{\mathrm{OBS}}\tau_{V}}{(1 - \mathrm{e}^{-\tau_{V}})} \mathrm{d}V$$

Molekul sa dva nivoa

- Nalazi se u polju zračenja J_ν sa T_B

$$S_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT_{ex}} - 1} = \frac{\int \phi_\nu J(T_R)_\nu + \varepsilon B_\nu(T_K)}{1+\varepsilon}$$

$$\varepsilon = \frac{C_{ji}}{A_{ji}}(1 - e^{-h\nu/kT_K})$$

$$\varepsilon = \frac{C_{ji}}{A_{ji}}\frac{h\nu}{kT_K}$$

- Uzimamo nekoliko aprox.

$$\int \phi_\nu J_\nu d\nu = J_\nu \int \phi_\nu d\nu = J_\nu(T_R)$$

$$S_\nu = (2k\nu^2)/c^2\, T_{ex},$$
$$J_\nu = (2k\nu^2)/c^2\, T_R$$
$$B_\nu = (2k\nu^2)/c^2\, T_K,$$

- Dobijamo: $T_{ex} = \dfrac{T_R + \varepsilon T_K}{1+\varepsilon}$
- Odnosno...

$$T_{ex} = T_K\left(\frac{T_0 + T_B}{T_0 + T_K}\right) \quad T_0 = \frac{h\nu}{k}\frac{C_{ul}}{A_{ul}}$$

Razmatranje molekula sa dva nivoa

- Kakav je oblik jednačine koju smo dobili?

$$T_{ex} = T_K \left(\frac{T_0 + T_B}{T_0 + T_K} \right) \quad T_0 = \frac{h\nu}{k} \frac{C_{ul}}{A_{ul}}$$

- Ukoliko su sudari dominantni:
  - T_0 je veliko i $T_{ex} \sim T_K$ (ravnoteža sudarima/LT)
- Ukoliko sudari nisu dovoljno česti:
  - T_0 je malo i $T_{ex} \sim T_B$ (ravnoteža zračenja)
- Bez dugotalasne aproksimacije

$$\frac{1}{e^{h\nu/kT_{ex}} - 1} = \frac{1}{1+\varepsilon} \frac{1}{[e^{h\nu/kT_R} - 1]} + \frac{\varepsilon}{1+\varepsilon} \frac{1}{[e^{h\nu/kT_K} - 1]}$$

Pojam kritične gustine

$$\frac{T_0}{T_{ex}} = \frac{T_0}{T_K} + \ln_e \left(\frac{e^{T_0/T_R} + \frac{C_{ji}}{A_{ji}}[e^{T_0/T_R} - 1]}{e^{T_0/T_K} + \frac{C_{ji}}{A_{ji}}[e^{T_0/T_R} - 1]} \right)$$

Procesi u MC

- Hladenje gasa
  - Rotacioni prelazi i emisione linije CO i drugih molekula
  - Sudari molekla sa hladnim česticama prešine
  - Emisija sudarno pobudenih linija [C ii], [Si ii] [C i]
  - Rotaciono-vibracione linje molekulskog vodonika
- Zagrevanje gasa (OB zvezde, difuzno polje zračenja)
  - Fotoelektricni mehanizam zagrevanja
  - UV-fluorescentno zagrevanje (Ly-Weiber fotoni)

Određivanje mase MC

- Džinsov zakon daje:

$$\mathcal{M}_{\rm J} = \frac{4\pi}{3} R_{\rm J}^3 \rho_{\rm c} \approx 18 \mathcal{M}_{\odot} T^{1.5} n^{-0.5}$$

- Na osnovu teoreme virijala:

$$\mathcal{M}_{\rm vir} \approx \Delta v^2 \left(\frac{R_{\rm c}}{G} \right) \qquad \Delta v = \sqrt{\frac{G\mathcal{M}_{\rm c}}{R_{\rm c}}}$$

- Na osnovu posmatranja CO:

$$L_{\rm CO} = D^2 \int I_{\rm CO} d\Omega \Leftrightarrow L_{\rm CO} = T_A^*({\rm CO}) \Delta v \pi R_{\rm c}^3$$

- **Konačna relacija:**

$$\boxed{L_{\rm CO} = T_A^*({\rm CO}) \left(\frac{3\pi G}{4\rho_{\rm c}} \right)^{1/2} \mathcal{M}_{\rm c}}$$

Odnos vodonika i CO?

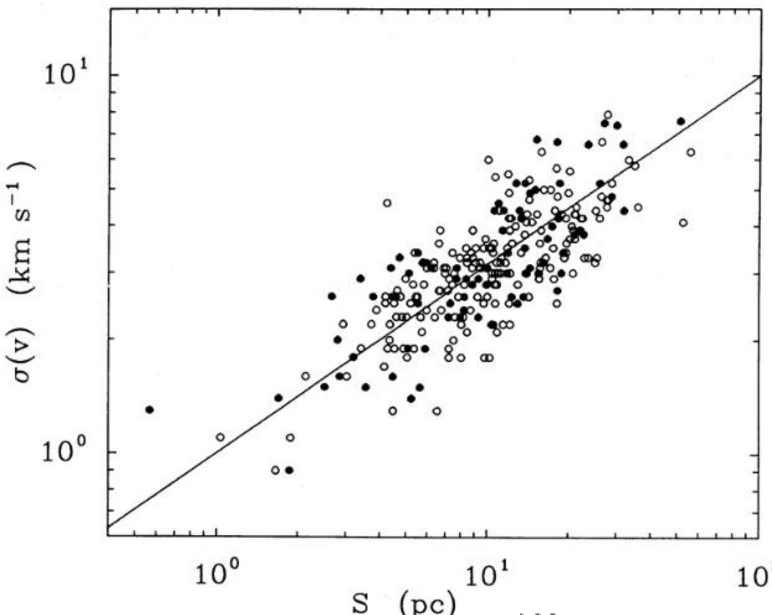
- Odnos se smatra konstantnim – određen je X faktorom u skladu sa formulom:

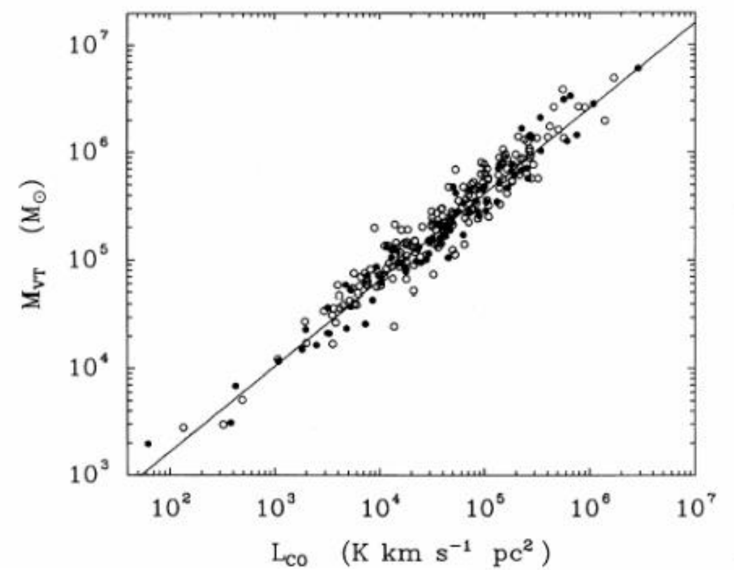
$$\frac{N(\mathrm{H_2})}{I_{\mathrm{CO}}} = X \cdot 10^{20}\ \mathrm{cm^{-2}}\ [\mathrm{K\ km\ s^{-1}}]$$

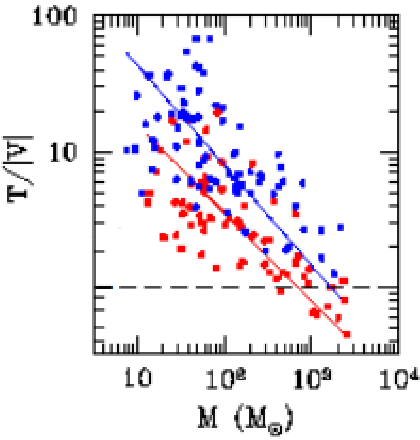
- Vrednosti dobijene za X variraju

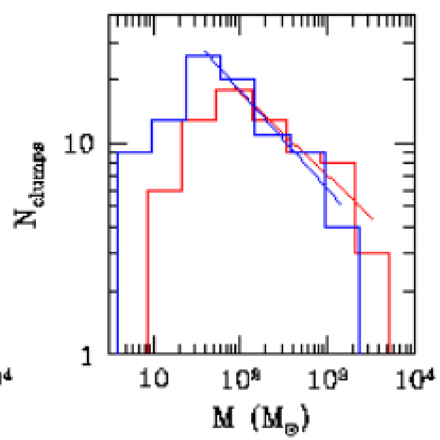
Early work	2-5
γ-rays Hunter et al. 1997	1.56 ±0.05
HI/IRAS/CO Dame et al. 2001	1.8±0.3
A_V Lada et al. 2003	~ 4

Emprijski zakoni









Solomon et al. 1987

Ključna pitanja

Ostaje nekoliko važnih tema koje nisu razjašnjene

- *Da li se GMC formiraju u spiralnim granama galaksija?*
- *Koji od svih procesa (sudari manjih molekulskih struktura, nestabilnost odnosa gravitacija - termalni gas, galaktički udarni talasi/najčešće supernova ostaci, magnetna polja) je najdominantniji u stvaranju molekulskih oblaka?*
- *Da li su sve površinske gustine u GMC iste ili bar približno iste?*
- *Možemo li strukturu GMC-a uopšititi kao diskretnu?*
- *Da li postoji veza izmedu fenomena dugog „životnog veka" spiralnih galaksija sa eventualnim dugim vremenom života molekulskih oblaka koji su zastupljeni u njima?*