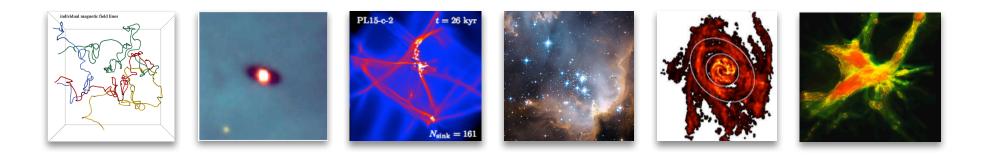
Challenges in Numerical Astrophysics Modeling Star Formation



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thanks to ...



... people in the group in Heidelberg:

Christian Baczynski, Erik Bertram, Frank Bigiel, Rachel Chicharro, Roxana Chira, Paul Clark, Gustavo Dopcke, Jayanta Dutta, Volker Gaibler, Simon Glover, Lukas Konstandin, Faviola Molina, Mei Sasaki, Jennifer Schober, Rahul Shetty, Rowan Smith, László Szűcs, Svitlana Zhukovska

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... many collaborators abroad!



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DFG







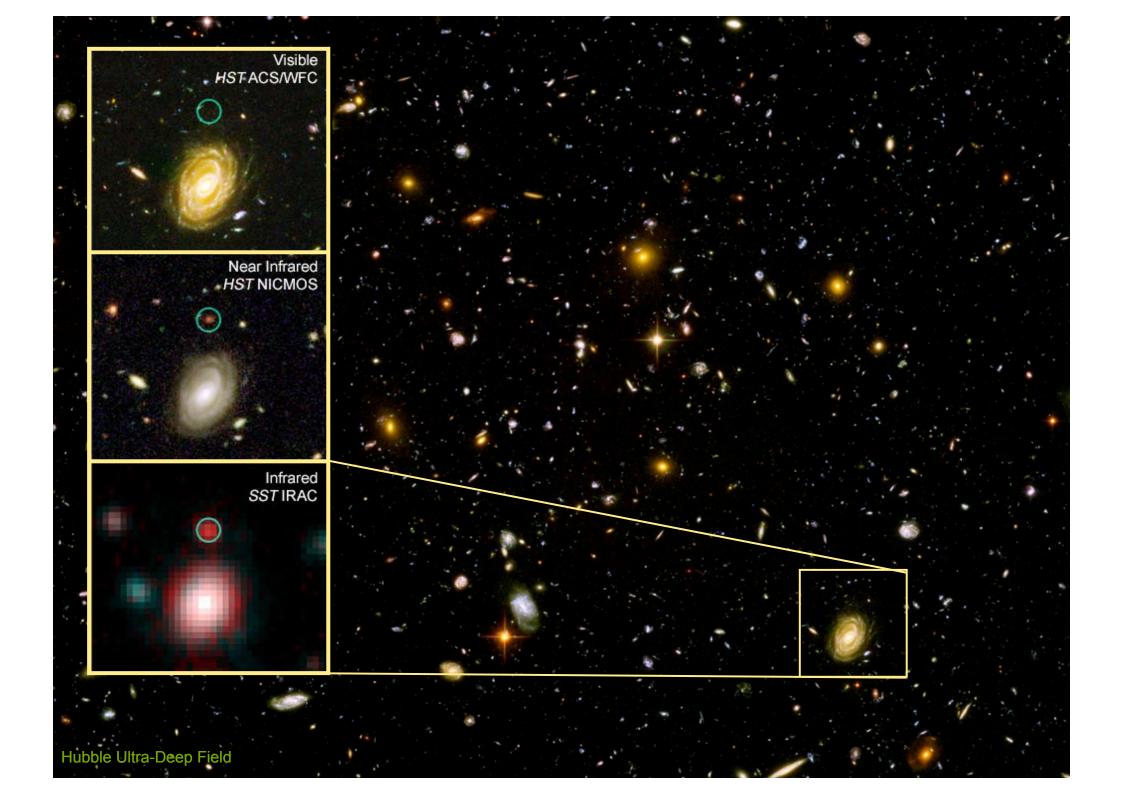


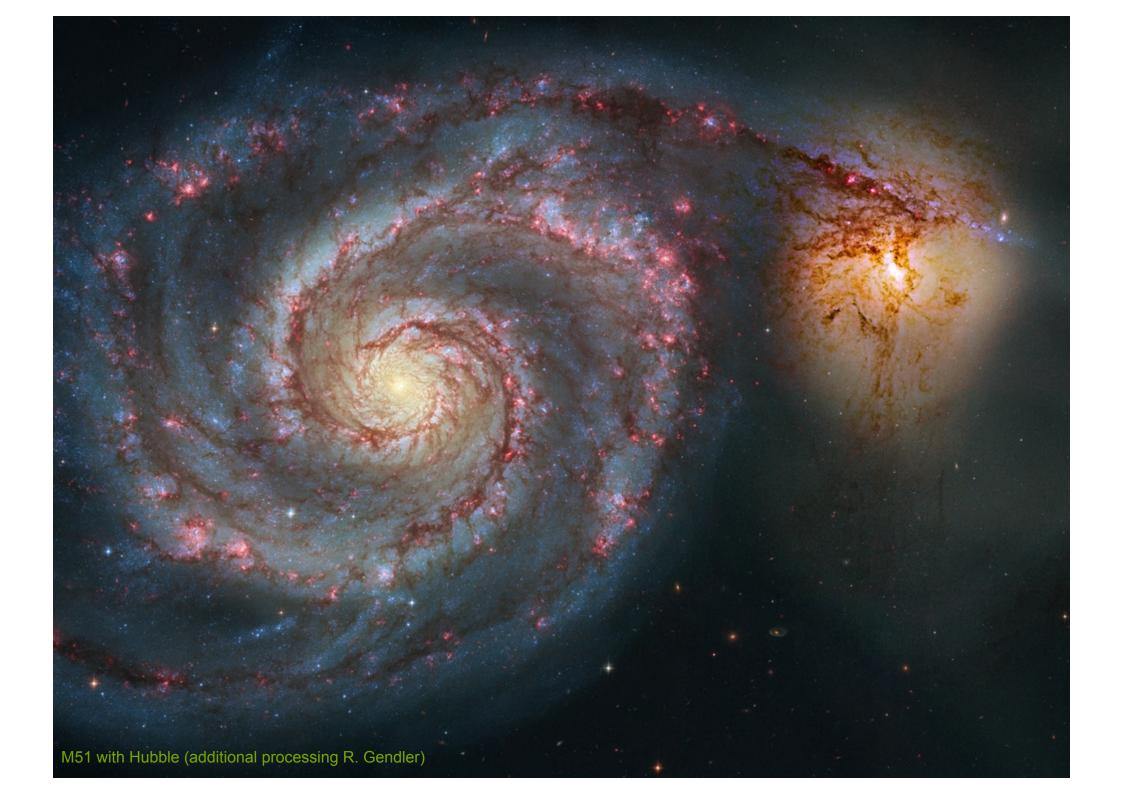
- phenomenology
- challenges
- approaches
 - (magneto)hydrodynamics
 - time-dependent chemistry
 - coupling to radiation field
- turbulence
- various feedback loops
- large dynamic range

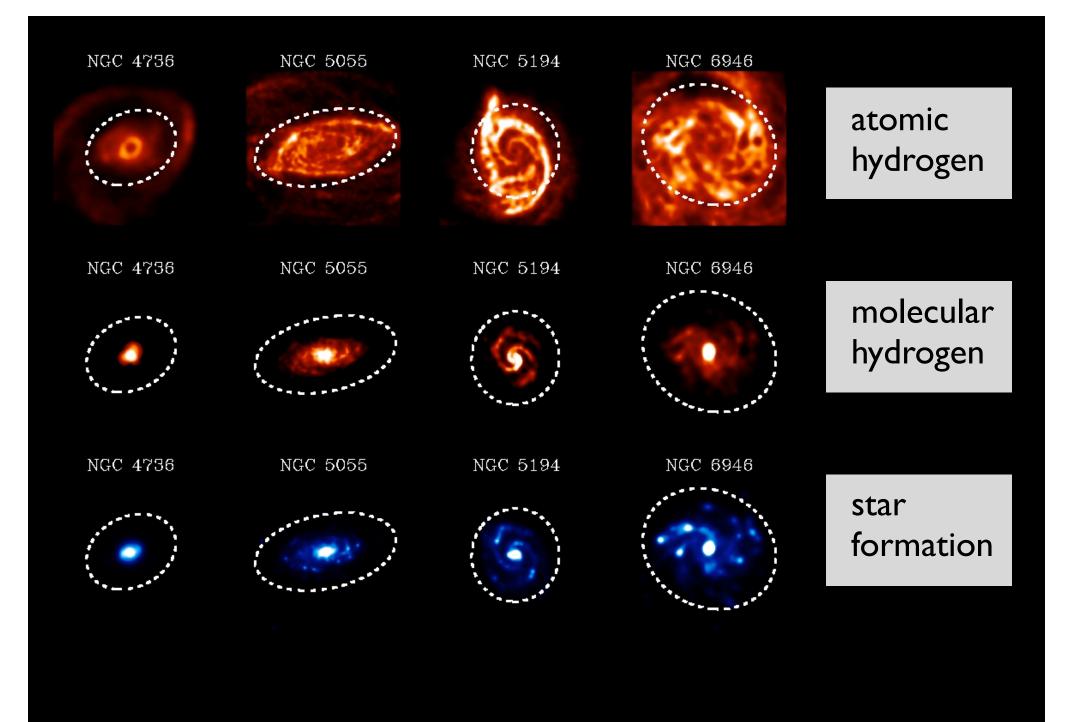


phenomenology

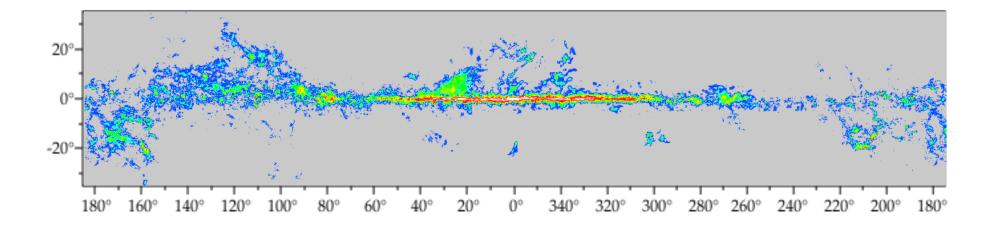






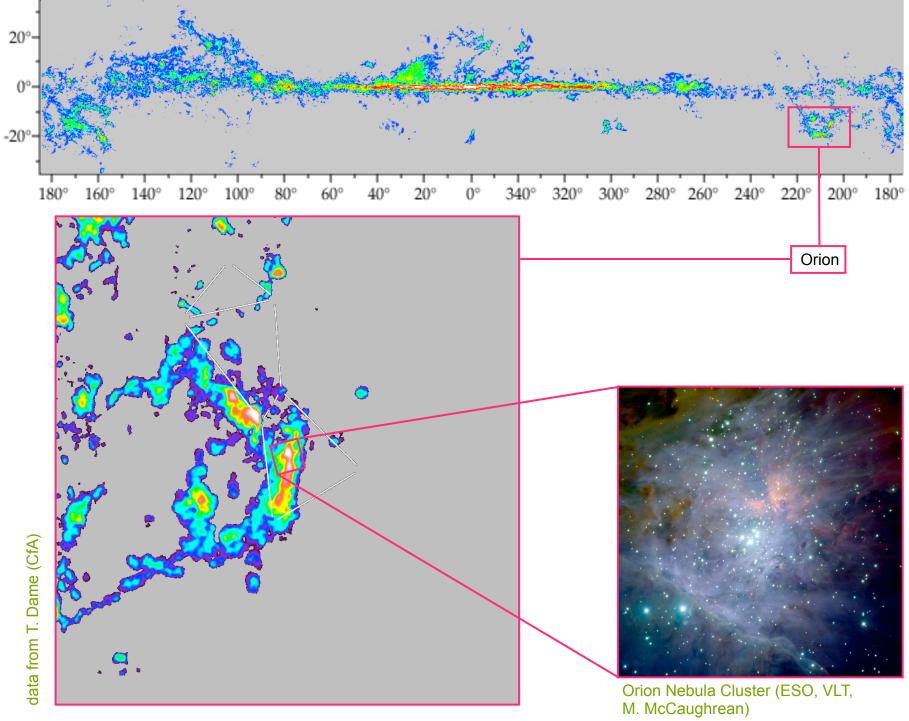


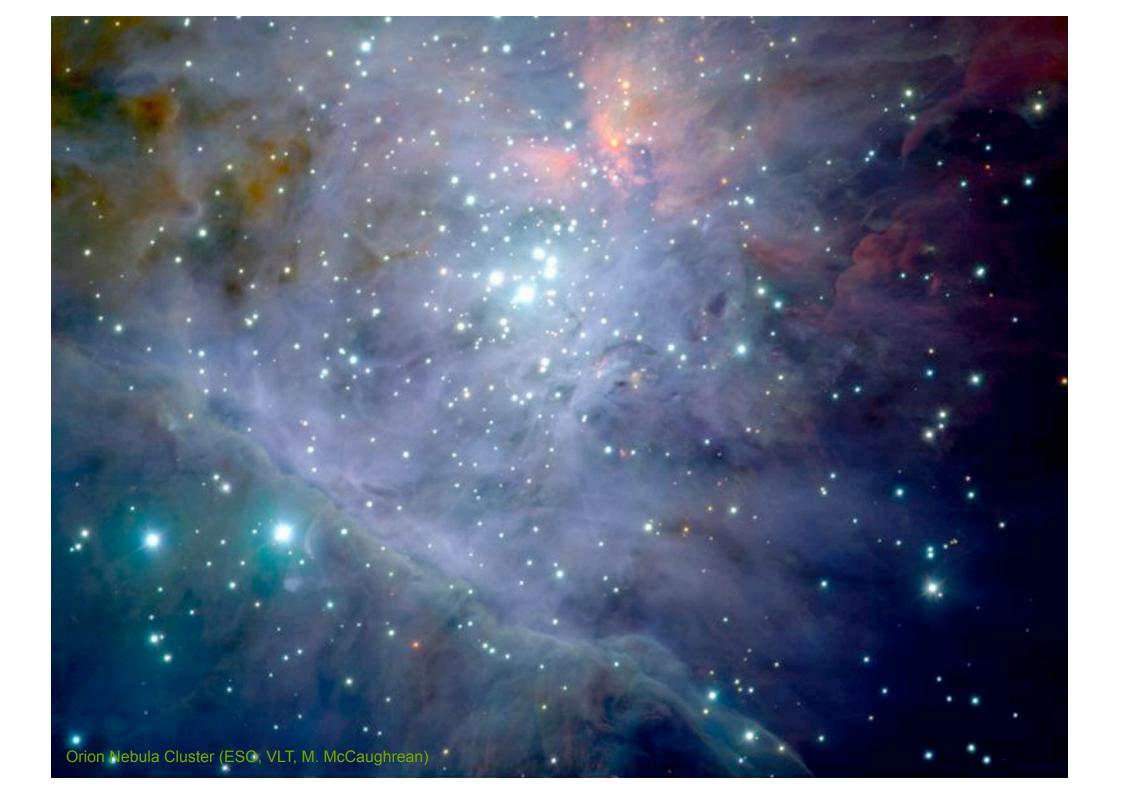
galaxies from THINGS and HERACLES survey (images from Frank Bigiel, ZAH/ITA)

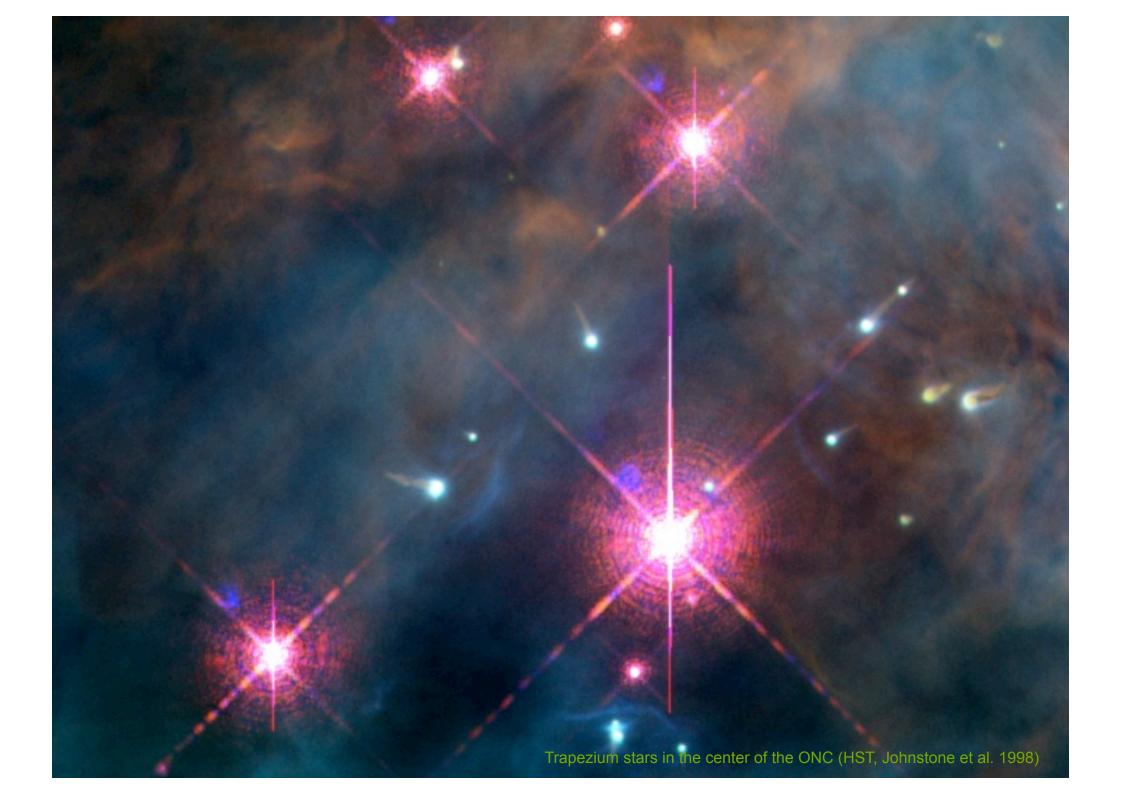


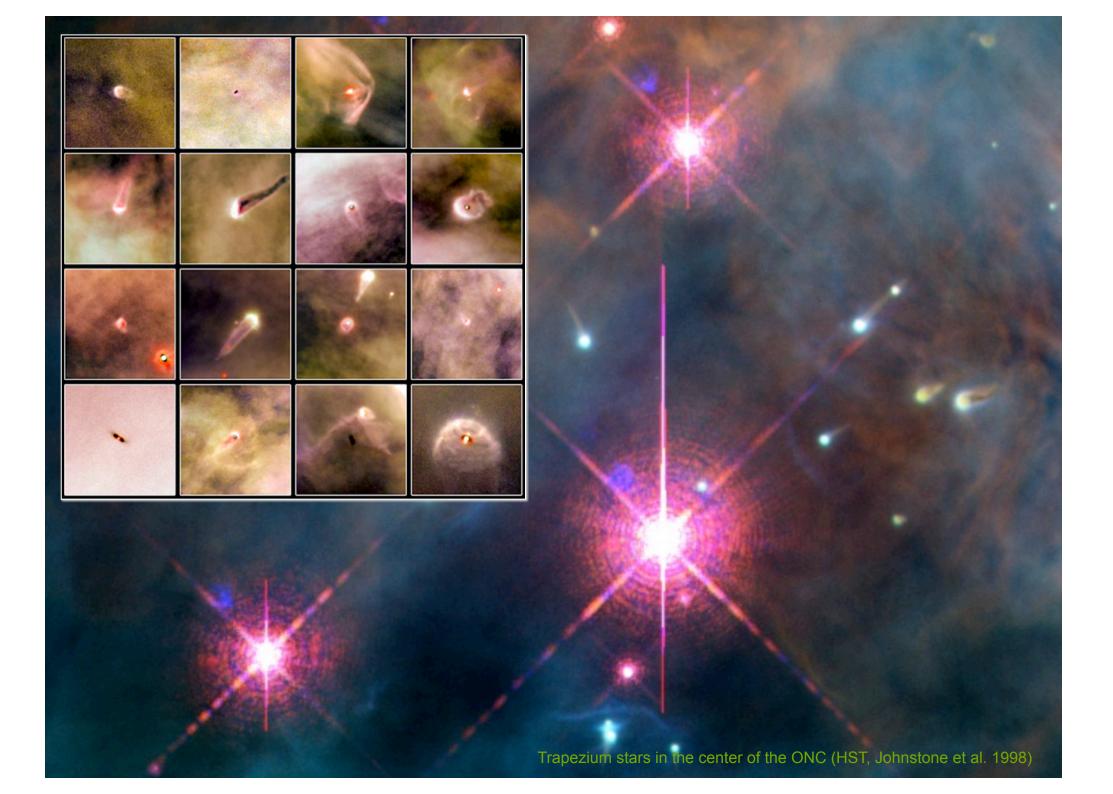
distribution of molecular gas in the Milky Way as traced by CO emission

data from T. Dame (CfA)







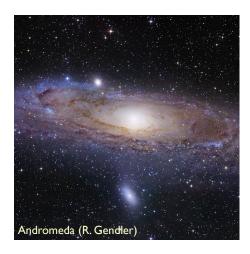


eventually, clusters like the ONC (1 Myr) will evolve into clusters like the Pleiades (100 Myr)

Pleiades (DSS, Palomar Observatory Sky Survey)



decrease in spatial scale / increase in density





Proplyd in Orion (Hubble)





- density
 - density of ISM: few particles per cm³
 - density of molecular cloud: few 100 particles per cm³
 - density of Sun: I.4 g/cm³
- spatial scale
 - size of molecular cloud: few 10s of pc
 - size of young cluster: ~ I pc
 - size of Sun: 1.4×10^{10} cm

decrease in spatial scale / increase in density





- contracting force
 - only force that can do this compression is **GRAVITY**
- Proplyd in Orion (Hubble)





- opposing forces
 - there are several processes that can oppose gravity
 - GAS PRESSURE
 - TURBULENCE
 - MAGNETIC FIELDS
 - RADIATION PRESSURE

Modern star formation theory is based on the complex interplay between *all* these processes.



Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Progress requires a comprehensive numerical approach.

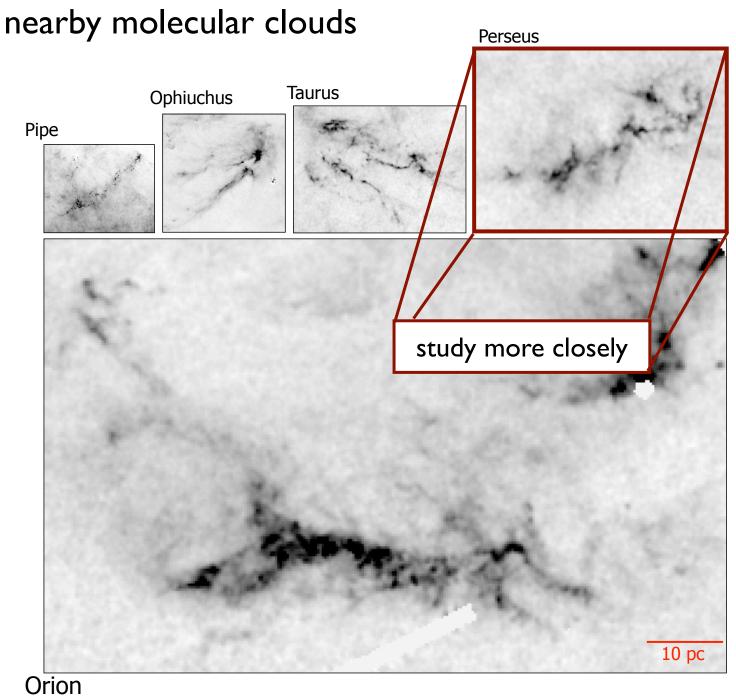
Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Progress requires a comprehensive numerical approach.

two selected examples

- formation and evolution of molecular clouds
 - combine MHD with self-gravity and time-dependent chemistry
 - model the turbulent multi-phase interstellar medium
- formation of massive stars
 - combining MHD with self-gravity, ionizing radiation, and subgrid scale models of (proto)stellar evolution
 - model the collapse of interstellar gas to build a star cluster

two selected examples

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(from A. Goodman)

scales to same scale

Rage COMPLETE Perseus

/iew size: 1305 × 733 /L: 63 WW: 127

mm peak (Enoch et al. 2006)

sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006

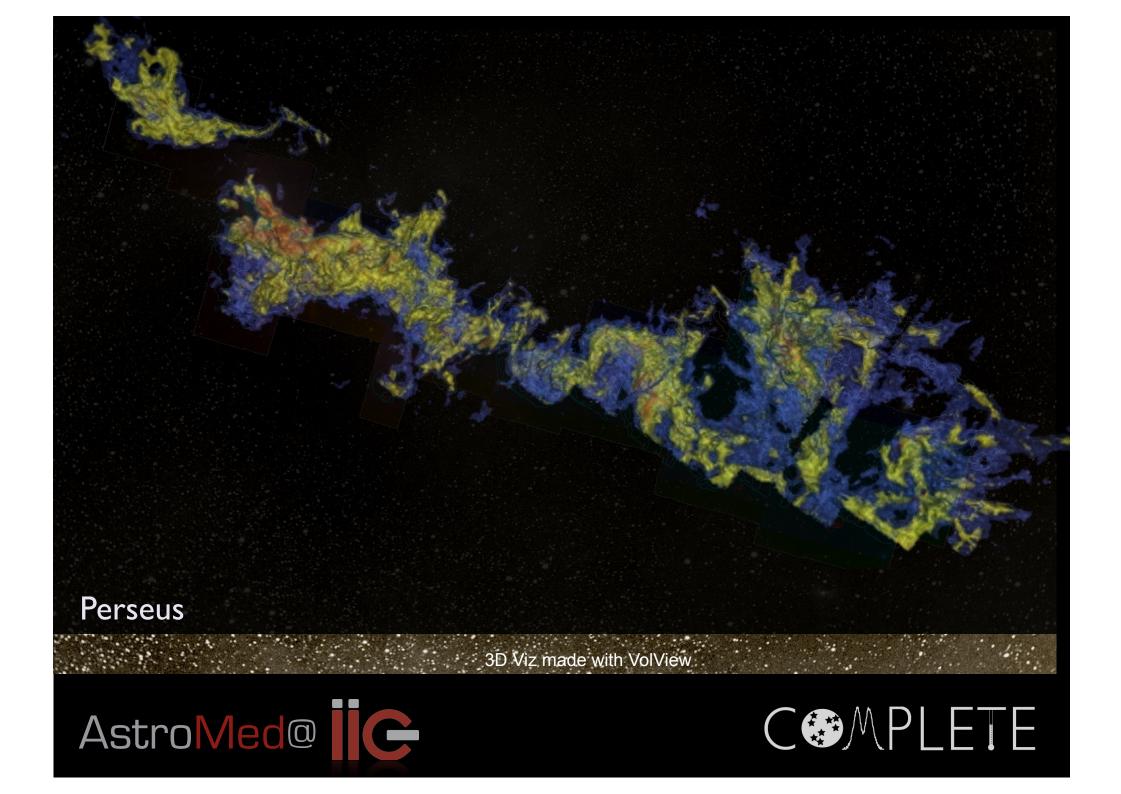
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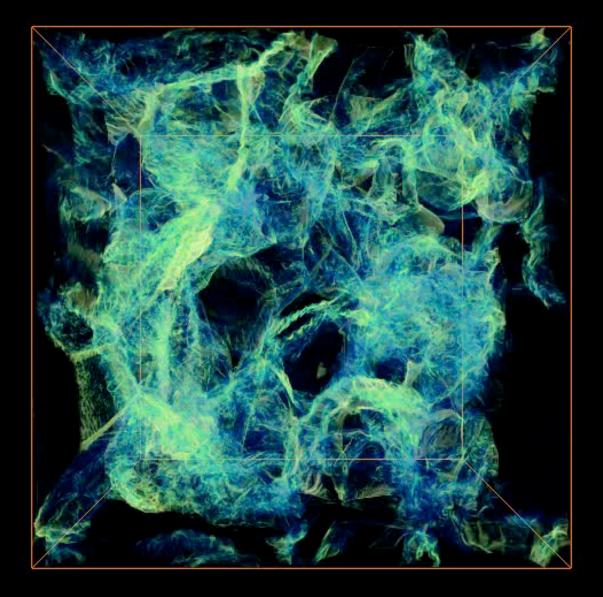
¹³CO (Ridge et al. 2006)

mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al. in prep.)

Optical image (Barnard 1927)

: 1/249 om: 227% Angle: 0

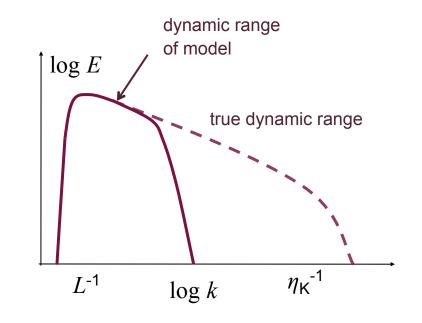




Schmidt et al. (2009, A&A, 494, 127)

large eddie simulations

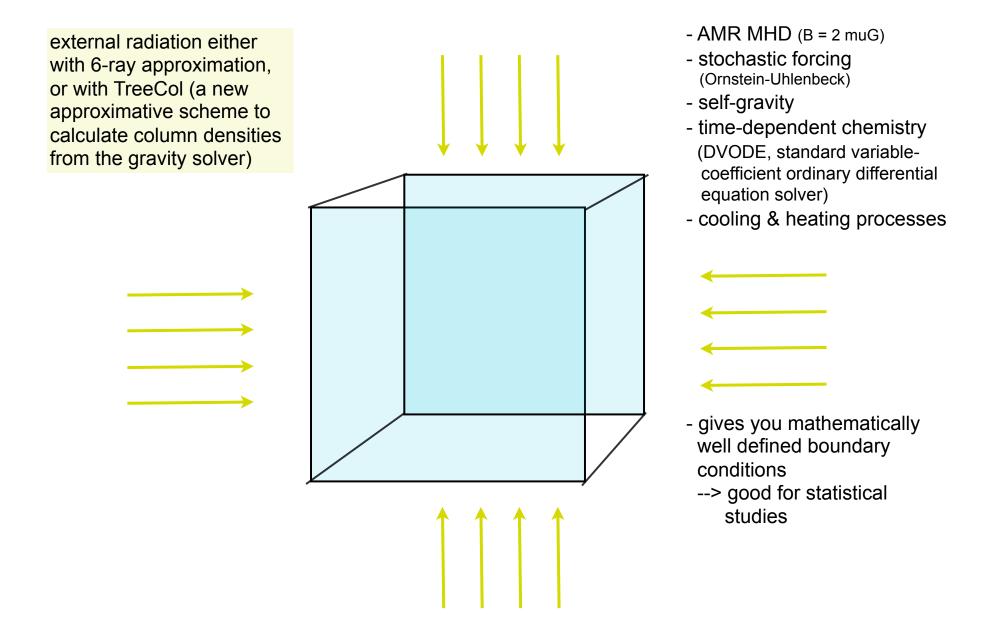
- We use *LES* to model the large-scale dynamics
- Principal problem: only large scale flow properties
 - Reynolds number: Re = LV/v (Re_{nature} >> Re_{model})
 - dynamic range much smaller than true physical one
 - need *subgrid model* (in our case simple: only dissipation)
 - but what to do for more complex when processes on subgrid scale determine large-scale dynamics (chemical reactions, nuclear burning, etc)
 - Turbulence is "space filling" --> difficulty for AMR (don't know what criterion to use for refinement)
- How *large* a Reynolds number do we need to catch basic dynamics right?







experimental set-up







chemical model 0

• 32 chemical species

•17 in instantaneous equilibrium:

 $\mathrm{H^{-},\ H_{2}^{+},\ H_{3}^{+},\ CH^{+},\ CH_{2}^{+},\ OH^{+},\ H_{2}O^{+},\ H_{3}O^{+},\ CO^{+},\ HOC^{+},\ O^{-},\ C^{-}\ and\ O_{2}^{+}}$

19 full non-equilibrium evolution

 $e^{-},\,H^{+},\,H,\,H_{2},\,He,\,He^{+},\,C,\,C^{+},\,O,\,O^{+},\,OH,\,H_{2}O,\,CO,$

 C_2 , O_2 , HCO^+ , CH, CH_2 and CH_3^+

218 reactions

various heating and cooling processes

⁽Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)



chemical model 1



Process	
Cooling:	
C fine structure lines	Atomic data – Silva & Viegas (2002) Collisional rates (H) – Abrahamsson, Krems & Dalgarno (2007) Collisional rates (H ₂) – Schroder et al. (1991) Collisional rates (e ⁻) – Johnson et al. (1987)
C ⁺ fine structure lines	Collisional rates (H ⁺) – Roueff & Le Bourlot (1990) Atomic data – Silva & Viegas (2002) Collisional rates (H ₂) – Flower & Launay (1977)
	Collisional rates (H, $T < 2000$ K) – Hollenbach & McKee (1989) Collisional rates (H, $T > 2000$ K) – Keenan et al. (1986) Collisional rates (e ⁻) – Wilson & Bell (2002)
O fine structure lines	Atomic data – Silva & Viegas (2002) Collisional rates (H) – Abrahamsson, Krems & Dalgarno (2007) Collisional rates (H ₂) – see Glover & Jappsen (2007) Collisional rates (e ⁻) – Bell, Berrington & Thomas (1998)
H ₂ rovibrational lines CO and H ₂ O rovibrational lines OH rotational lines Gas-grain energy transfer Recombination on grains Atomic resonance lines H collisional ionization H ₂ collisional dissociation Compton cooling	Collisional rates (H ⁺) – Pequignot (1990, 1996) Le Bourlot, Pineau des Forêts & Flower (1999) Neufeld & Kaufman (1993); Neufeld, Lepp & Melnick (1995) Pavlovski et al. (2002) Hollenbach & McKee (1989) Wolfire et al. (2003) Sutherland & Dopita (1993) Abel et al. (1997) See Table B1 Cen (1992)
Heating: Photoelectric effect H ₂ photodissociation UV pumping of H ₂ H ₂ formation on dust grains Cosmic ray ionization	Bakes & Tielens (1994); Wolfire et al. (2003) Black & Dalgarno (1977) Burton, Hollenbach & Tielens (1990) Hollenbach & McKee (1989) Goldsmith & Langer (1978)





No.	Reaction	chemical mo	$)(] \in$	l ef.
1	$H + e^- \rightarrow H^- + \gamma$	$k_1 = \text{dex}[-17.845 + 0.762 \log T + 0.1523 (\log T)^2$		
		$-0.03274(\log T)^3$	$T \leqslant 0000 \ { m K}$	
		$= dex[-16.420 + 0.1998(log T)^2$		
		$-5.447 \times 10^{-3} (\log T)^4$ + 4.0415 × 10 ⁻⁵ (log T) ⁶]	$T > 6000 { m K}$	
2	$H^- + H \rightarrow H_2 + e^-$	$k_2 = 1.5 \times 10^{-9}$	$T \leq 300 \text{ K}$	2
		$= 4.0 \times 10^{-9} T^{-0.17}$	T > 300 K	
3	$H + H^+ \rightarrow H_2^+ + \gamma$	$k_3 = dex[-19.38 - 1.523 \log T]$		3
		$+ 1.118(\log T)^2 - 0.1269(\log T)^3$		
4	$H + H_2^+ \rightarrow H_2 + H^+$	$k_4 = 6.4 \times 10^{-10}$		4
5 6	$H^- + H^+ \rightarrow H + H$ $H_2^+ + e^- \rightarrow H + H$	$k_5 = 2.4 \times 10^{-6} T^{-1/2} (1.0 + T/20000)$ $k_6 = 1.0 \times 10^{-8}$	$T \leqslant 617 \text{ K}$	5 6
0	$n_2 + e \rightarrow n + n$	$= 1.32 \times 10^{-6} T^{-0.76}$	$T \ge 617 \text{ K}$ $T \ge 617 \text{ K}$	0
7	$H_2 + H^+ \rightarrow H_2^+ + H$	$k_7 = [-3.3232183 \times 10^{-7}]$	- ,	7
		$+3.3735382 \times 10^{-7} \ln T$		
		$-1.4491368 \times 10^{-7} (\ln T)^2$		
		$+ 3.4172805 \times 10^{-8} (\ln T)^3$		
		$-4.7813720 \times 10^{-9} (\ln T)^4$ + 3.9731542 × 10 ⁻¹⁰ (ln T) ⁵		
		$-1.8171411 \times 10^{-11} (\ln T)^6$		
		$+3.5311932 \times 10^{-13} (\ln T)^{7}$		
		$\times \exp \left(\frac{-21237.15}{T} \right)$		
8	$\rm H_2 + e^- \rightarrow \rm H + \rm H + e^-$	$k_8 = 3.73 \times 10^{-9} T^{0.1121} \exp\left(\frac{-99430}{T}\right)$		8
9	$\rm H_2 + \rm H \rightarrow \rm H + \rm H + \rm H$	$k_{9,1} = 6.67 \times 10^{-12} T^{1/2} \exp \left[-(1 + \frac{63590}{T})\right]$		9
		$k_{9,h} = 3.52 \times 10^{-9} \exp \left(-\frac{43600}{T}\right)$		10
		$n_{cr,H} = dex \left[3.0 - 0.416 \log \left(\frac{T}{10000} \right) - 0.327 \left\{ log \left(\frac{T}{10000} \right) \right\}^2 \right]$		10
10	$H_2 + H_2 \rightarrow H_2 + H + H$	$k_{10,1} = \frac{5.996 \times 10^{-30} T^{4.1881}}{(1.0+6.761 \times 10^{-6} T)^{5.6881}} \exp\left(-\frac{54657.4}{T}\right)$		11
		$k_{10,h} = 1.3 \times 10^{-9} \exp\left(-\frac{53300}{T}\right)$		12
		$n_{\rm cr,H_2} = \text{dex} \left[4.845 - 1.3 \log \left(\frac{T}{10000} \right) + 1.62 \left\{ \log \left(\frac{T}{10000} \right) \right\}^2 \right]$		12
11	$\rm H + e^- \rightarrow \rm H^+ + e^- + e^-$	$k_{11} = \exp[-3.271396786 \times 10^{1}]$		13
		$+ 1.35365560 \times 10^{1} \ln T_{e}$		
		$-5.73932875 \times 10^{0} (\ln T_{e})^{2}$ + 1.56315498 × 10 ⁰ (ln T _e) ³		
		$+ 1.56510498 \times 10^{-1} (\ln T_e)^4$ $- 2.87705600 \times 10^{-1} (\ln T_e)^4$		
		$+3.48255977 \times 10^{-2} (\ln T_e)^5$		
		$-2.63197617 \times 10^{-3} (\ln T_e)^6$		
		$+ 1.11954395 \times 10^{-4} (\ln T_e)^7$		
		$-2.03914985 \times 10^{-6} (\ln T_e)^8$	<i>.</i> .	
12	$\rm H^+ + e^- \rightarrow \rm H + \gamma$	$k_{12,\Lambda} = 1.269 \times 10^{-13} \left(\frac{315614}{T}\right)^{1.503} \\ \times [1.0 + \left(\frac{604625}{T}\right)^{0.470}]^{-1.923}$	Case A	14
		$k_{12,B} = 2.753 \times 10^{-14} \left(\frac{315614}{T}\right)^{1.500}$	Case B	14
		$\times \left[1.0 + \left(\frac{115188}{T}\right)^{0.407}\right]^{-2.242}$		
13	$\rm H^- + e^- \rightarrow \rm H + e^- + e^-$	$k_{13} = \exp[-1.801849334 \times 10^{1}]$		13
		$+ 2.36085220 \times 10^{0} \ln T_{e}$ $- 2.82744300 \times 10^{-1} (\ln T_{e})^{2}$		
		$+ 1.62331664 \times 10^{-2} (\ln T_e)^3$		
		$-3.36501203 \times 10^{-2} (\ln T_e)^4$		
		$+ 1.17832978 \times 10^{-2} (\ln T_e)^5$		
		$-1.65619470 \times 10^{-3} (\ln T_e)^6$ + $1.06827520 \times 10^{-4} (\ln T_e)^7$		



		14	$\rm H^- + \rm H \rightarrow \rm H + \rm H + e^-$	$k_{14} = 2.5634 \times 10^{-9} T_{e}^{1.78186}$	$T_{\rm e} \leqslant 0.1 {\rm eV}$	13
				$= \exp[-2.0372609 \times 10^{1}]$		
Table	B1			+ $1.13944933 \times 10^{0} \ln T_{e}$ - $1.4210135 \times 10^{-1} (\ln T_{e})^{2}$		
Table	D1.			$+ 8.4644554 \times 10^{-3} \text{ n } T_e)^3$		
No.	Rea		che	$-1.37641 \times 10^{-3} \ln T_{e}$	el 2	
	_					
1	н+			$+ 8.6639632 \times 10^{-5} (\ln T_c)^6$		
				$-2.5850097 \times 10^{-5} (\ln T_e)^7$ + 2.4555012 × 10^{-6} (\ln T_e)^8		
				$-8.0683825 \times 10^{-8} (\ln T_e)^9$	$T_{\rm e} > 0.1 {\rm eV}$	
		15	$\mathrm{H^-} + \mathrm{H^+} \rightarrow \mathrm{H_2^+} + \mathrm{e^-}$	$k_{15} = 6.9 \times 10^{-9} T^{-0.35}$	$T \leq 8000 \text{ K}$	15
2	H^{-}		*	$= 9.6 \times 10^{-7} T^{-0.90}$	$T > 8000 { m K}$	
_		16	$\mathrm{He} + \mathrm{e}^- \rightarrow \mathrm{He}^+ + \mathrm{e}^- + \mathrm{e}^-$	$k_{16} = \exp[-4.409864886 \times 10^{1}]$		13
3	н+			$+ 2.391596563 \times 10^{1} \ln T_{e}$		
4	H +			$-1.07532302 \times 10^{1} (\ln T_{e})^{2}$ + 3.05803875 × 10 ⁰ (ln T _e) ³		
5	н-			$-5.6851189 \times 10^{-1} (\ln T_e)^4$		
6	H_2^+			$+ 6.79539123 \times 10^{-2} (\ln T_e)^5$		
				$-5.0090561 \times 10^{-3} (\ln T_e)^6$		
7	H_2 ·			$+ 2.06723616 \times 10^{-4} (\ln T_e)^7$ $- 3.64916141 \times 10^{-6} (\ln T_e)^8$]		
		17	$He^+ + e^- \rightarrow He + \gamma$	$-3.64916141 \times 10^{-6} (\ln T_e)^{-6}$ $k_{17,rr,A} = 10^{-11} T^{-0.5} [12.72 - 1.615 \log T]$	Case A	16
			$10^{\circ} + 0^{\circ} \rightarrow 10^{\circ} + 7$	$-0.3162(\log T)^2 + 0.0493(\log T)^3$	Cabe A	10
				$k_{17,rr,B} = 10^{-11}T^{-0.5} [11.19 - 1.676 \log T]$	Case B	16
				$-0.2852(\log T)^2 + 0.04433(\log T)^3$		
				$k_{17,di} = 1.9 \times 10^{-3} T^{-1.5} \exp\left(-\frac{473421}{T}\right)$		
				$\times \left[1.0 \pm 0.3 \exp \left(- \frac{94684}{6} \right) \right]$		17
		18	$\mathrm{He^+} + \mathrm{H} \rightarrow \mathrm{He} + \mathrm{H^+}$	$k_{18} = 1.25 \times 10^{-15} \left(\frac{T}{300}\right)^{0.25} r^{-7/3}$ $k_{18} = 1.05 \times 10^{-9} r^{-0.75} \exp\left(-127500\right)$		18
8	H_2 .	19	${\rm He} + {\rm H}^+ \rightarrow {\rm He}^+ + {\rm H}$	$k_{19} = 1.26 \times 10^{-9} T^{-0.75} \exp\left(-\frac{127500}{\pi}\right)$	$T \le 10000 \text{ K}$	19
9	H_2 ·			$=4.0 \times 10^{-37} T^{4.74}$	T > 10000 K	
		20	$C^+ + e^- \rightarrow C + \gamma$	$k_{20} = 4.67 \times 10^{-12} \left(\frac{T}{300}\right)^{-0.6}$	$T \leqslant 7950 \text{ K}$	20
				$ \begin{array}{l} \kappa_{20} = 4.67 \times 10^{-17} \left(\frac{1}{300}\right)^{2.49} \exp\left(\frac{21845.6}{T}\right) \\ = 1.23 \times 10^{-17} \left(\frac{T}{300}\right)^{-1.37} \exp\left(\frac{-115786.2}{T}\right) \end{array} $	$7950~{\rm K} < T \leqslant 21140~{\rm K}$	
10	H_2 .			$=9.62 \times 10^{-8} \left(\frac{1}{300}\right)^{-1.37} \exp\left(\frac{-115786.2}{T}\right)$	T > 21140 K	
		21	$O^+ + e^- \rightarrow O + \gamma$	$k_{21} = 1.30 \times 10^{-10} T^{-0.64}$	$T \leq 400 \text{ K}$	21
				$= 1.41 \times 10^{-10} T^{-0.66} + 7.4 \times 10^{-4} T^{-1.5}$		
				$\times \exp \left(-\frac{175000}{T}\right) \left[1.0 + 0.062 \times \exp \left(-\frac{145000}{T}\right)\right]$	$T > 400 { m K}$	
11	Н+	22	$C + e^- \rightarrow C^+ + e^- + e^-$	$k_{22} = 6.85 \times 10^{-8} (0.193 + u)^{-1} u^{0.25} e^{-u}$	$u = 11.26/T_{e}$	22
		23	$O + e^- \rightarrow O^+ + e^- + e^-$	$k_{23} = 3.59 \times 10^{-8} (0.073 + u)^{-1} u^{0.34} e^{-u}$	$u = 13.6/T_{e}$	22
		24 25	$O^+ + H \rightarrow O + H^+$ $O + H^+ \rightarrow O^+ + H$	$\begin{aligned} k_{24} &= 4.99 \times 10^{-11} T^{0.405} + 7.54 \times 10^{-10} T^{-0.458} \\ k_{25} &= [1.08 \times 10^{-11} T^{0.517} \end{aligned}$		23 24
		20	$0 + H^{*} \rightarrow 0^{*} + H$	$\kappa_{25} = [1.08 \times 10^{-1} T + 4.00 \times 10^{-10} T^{0.00669}] \exp\left(-\frac{227}{T}\right)$		24
		26	$O + He^+ \rightarrow O^+ + He$	$k_{26} = 4.991 \times 10^{-15} \left(\frac{T}{10000}\right)^{0.3794} \exp\left(-\frac{T}{1121000}\right)$		25
		20	0 + ne - 0 · + ne	$(10000) = (1001 \times 10^{-15} (T)^{-0.2163} = (T)^{-0.2163}$		20
		27	$C + H^+ \rightarrow C^+ + H$	$ \begin{array}{c} \exp\left(-\frac{1121000}{1121000}\right) \\ + 2.780 \times 10^{-15} \left(\frac{T}{10000}\right)^{-0.2163} \exp\left(\frac{T}{815800}\right) \\ k_{27} = 3.9 \times 10^{-16} T^{0.213} \end{array} $		24
12	H^+	27	$C + H^+ \rightarrow C^+ + H^+$ $C^+ + H \rightarrow C + H^+$	$h_{27} = 0.0 \times 10^{-14} \left(\frac{T}{T} \right)^{1.96} \text{ sum} \left(170000 \right)$		24 24
		28	$C^+ H^- \rightarrow C^+ H^-$ $C^+ He^+ \rightarrow C^+ + He^-$	$ k_{28} = 6.08 \times 10^{-14} \left(\frac{T}{10000}\right)^{1.96} \exp\left(-\frac{170000}{T}\right) k_{29} = 8.58 \times 10^{-17} T^{0.757}_{-0.757} $	$T \leqslant 200 \text{ K}$	24 26
		20	o, ne ⇒o +ne	$= 3.25 \times 10^{-17} T^{0.968}$	$200 < T \le 200$ K	20
				$= 2.77 \times 10^{-19} T^{1.597}$	$T > 2000 { m K}$	
12		30	$\rm H_2 + He \rightarrow H + H + He$	$k_{30,1} = \text{dex} \left[-27.029 + 3.801 \log (T) - 29487/T\right]$		27
13	н-			$k_{30,h} = \text{dex} \left[-2.729 - 1.75 \log (T) - 23474/T \right]$		07
			0	$n_{\rm cr,He} = \text{dex} \left[5.0792(1.0 - 1.23 \times 10^{-5}(T - 2000)) \right]$		27
		31	$OH + H \rightarrow O + H + H$ $HOO^{+} + H_{2} \rightarrow HOO^{+} + H_{2}$	$k_{31} = 6.0 \times 10^{-9} \exp\left(-\frac{50900}{T}\right)$ $k_{32} = 3.8 \times 10^{-10}$		28
		32 33	$HOC^+ + H_2 \rightarrow HCO^+ + H_2$ $HOC^+ + CO \rightarrow HCO^+ + CO$	$k_{32} = 3.8 \times 10^{-10}$ $k_{33} = 4.0 \times 10^{-10}$		29 30
		34	$C + H_2 \rightarrow CH + H$			31
		35	$CH + H \rightarrow C + H_2$	$k_{34} = 6.64 \times 10^{-10} \exp \left(-\frac{11700}{T}\right)$ $k_{35} = 1.31 \times 10^{-10} \exp \left(-\frac{80}{T}\right)$		32
		_		T(T)		







		14	Н	+ H -	• H + H + e ⁻	$k_{14} = 2.5634 \times 10^{-9} T_{\rm e}^{1.78186}$	$T_e \leqslant 0.1 \text{ eV}$	
	-			36	$\rm CH + \rm H_2 \rightarrow \rm CH_2 +$			
lable	B1. 1			37	$CH + C \rightarrow C_2 + H$		34	
	_			38	$CH + C \rightarrow CO + 1$		T = 2000 - 6 - 35	
No.	Rea					$= 1.00 \times 0^{-10} \text{ xp} - \frac{1}{7}$		
1	H +			39	$CH_2 + O \rightarrow CO +$	H_{\pm} H_{\pm} $K_{40} = 1.33 \times 10^{-10}$		
-				40 41	$CH_2 + O \rightarrow CO +$ $CH_2 + O \rightarrow CO +$		39	
				42	$C_2 + O \rightarrow CO + C$	$h_{12} = 5.0 \times 10^{-11} (T)^{0.5}$	$T \le 300 \text{ K}$ 40	
				42	$C_2 + 0 \rightarrow C0 + C$	$\kappa_{42} = 5.0 \times 10^{-11} \left(\frac{300}{7} \right)^{0.757}$		
-		15	H^{-}			$k_{42} = 5.0 \times 10^{-11} \left(\frac{T}{300}\right)^{0.5} = 5.0 \times 10^{-11} \left(\frac{T}{300}\right)^{0.757} = 5.0 \times 10^$	T > 300 K 41	
2	н-	10		43	$O + H_2 \rightarrow OH + H_2$	$k_{43} = 3.14 \times 10^{-13} \left(\frac{1}{300}\right)^{-13} \text{es}$	$xp\left(-\frac{3150}{T}\right)$ 42	
3	H +	16	He	44	$OH + H \rightarrow O + H_2$		$xp(-\frac{1950}{T})$ 43	
0				45	$OH + H_2 \rightarrow H_2O$	$+ H = k_{45} = 2.05 \times 10^{-12} \left(\frac{T}{300} \right)^{-10} e^{-12}$	$\exp\left(-\frac{1736}{T}\right)$ 44	
4	H +			46	$OH + C \rightarrow CO + H$	$\kappa_{46} = 1.0 \times 10$	34	
5	H^{-}			47	$OH + O \rightarrow O_2 + H$		$T \le 261 \text{ K}$ 45	
6	H_2^+					$= 1.77 \times 10^{-11} \exp \left(\frac{178}{T}\right)$	T > 261 K 33	
-				48	$OH + OH \rightarrow H_2O$	$+ H = k_{48} = 1.65 \times 10^{-12} \left(\frac{1}{300} \right) = 6$	$\exp(-\frac{50}{T})$ 34	
7	H ₂ ·			49	$H_2O + H \rightarrow H_2 + f$	OH $k_{49} = 1.59 \times 10^{-11} \left(\frac{T}{300}\right)^{1.2} estimates$	$xp(-\frac{9610}{T})$ 46	
		17	He	50	$O_2 + H \rightarrow OH + C$			
				51	$O_2 + H_2 \rightarrow OH +$		<u>eó</u>) 47	
				52	$O_2 + C \rightarrow CO + C$	-0.24	$T \le 295 \text{ K}$ 34	
				02	$0_2 + 0 \rightarrow 00 + 0$	$x_{32} = 4.1 \times 10^{-12} (300)$	(613) T > 005 K 22	
				_	~ ~ ~ ~	$= 2.48 \times 10^{-12} \left(\frac{T}{300}\right)^{1.54} e^{-10}$	$\exp\left(\frac{613}{T}\right)$ T > 295 K 33	
				53	$CO + H \rightarrow C + OH$	H $k_{53} = 1.1 \times 10^{-10} \left(\frac{T}{300}\right)_{0.042}^{0.5} exp$	$p\left(-\frac{T}{T}\right)$ 28	
_		18	He	54	$H_2^+ + H_2 \rightarrow H_3^+ +$		$\exp\left(-\frac{T}{46600}\right)$ 48	
8	H_2 ·	19	He	55	$H_3^+ + H \rightarrow H_2^+ + H$) 49	
9	H_2	10		56	$C + H_2^+ \rightarrow CH^+ +$		28	
		20	C^+	57	$C + H_3^+ \rightarrow CH^+ +$		28	
			~ I	58	$C^+ + H_2 \rightarrow CH^+$. 1	/	
10	H_2 ·			59	$CH^+ + H \rightarrow C^+ +$	-	51	
10	112.		~		$CH^+ + H_2 \rightarrow CH_2^+$		51	
		21	0+	61 62	$CH^+ + O \rightarrow CO^+$ $CH_2 + H^+ \rightarrow CH^+$		52 28	
				63	$CH_2^+ + H \rightarrow CH^+$ $CH_2^+ + H \rightarrow CH^+$		28	
11	H +	22	C+	64	$CH_2 + H \rightarrow CH^+$ $CH_2^+ + H_2 \rightarrow CH_3^+$		20 53	
		22	01	65	$CH_2 + H_2 \rightarrow CH_3$ $CH_2^+ + O \rightarrow HCO$		28	
		24	ŏ+	66	$CH_2^+ + U \rightarrow HCU$ $CH_3^+ + H \rightarrow CH_2^+$			
		25	0+	67	$CH_3^+ + O \rightarrow HCO$ $CH_3^+ + O \rightarrow HCO$	$+ H_2$ $k_{67} = 4.0 \times 10^{-10}$ exp (- T	54	
				68	$C_2 + O^+ \rightarrow CO^+$		28	
		26	0+	69	$O^+ + H_2 \rightarrow OH^+$		55	
				70	$O + H_2^+ \rightarrow OH^+ +$		28	
		27	C+	71	$O + H_3^+ \rightarrow OH^+ +$	$H_2 = k_{71} = 8.4 \times 10^{-10}$	56	
12	H^+	28	C+	72	$OH + H_3^+ \rightarrow H_2O^+$	$+ H_2 = 1.3 \times 10^{-9}$	28	
		28 29	C+	73	$OH + C^+ \rightarrow CO^+$		28	
		29	04		$OH^+ + H_2 \rightarrow H_2O$		57	
				75 76	$H_2O^+ + H_2 \rightarrow H_3$ $H_2O^+ + H_2 \rightarrow H_2O^+$		58	
		30	H_2	76 77	$H_2O + H_3^+ \rightarrow H_3O$ $H_2O + C^+ \rightarrow HCO$		59 60	
13	н-			78	$H_2O + C^+ \rightarrow HOO$ $H_2O + C^+ \rightarrow HOO$		60	
				79	$H_3O^+ + C \rightarrow HCO$	$D^+ + H_2$ $k_{79} = 1.0 \times 10^{-11}$	28	
		31	OH	80	$O_2 + C^+ \rightarrow CO^+$	+ O $k_{80} = 3.8 \times 10^{-10}$	53	
		32	HO	81	$O_2 + C^+ \rightarrow CO +$	O^+ $k_{81} = 6.2 \times 10^{-10}$	53	
		33	но	82	$O_2 + CH_2^+ \rightarrow HCC$	$D^+ + OH$ $k_{82} = 9.1 \times 10^{-10}$	53	
		34	C +	83	$O_2^+ + C \rightarrow CO^+ +$	O $k_{83} = 5.2 \times 10^{-11}$	28	
		35	CH	84	$CO + H_3^+ \rightarrow HOC$	$^{+}$ + H ₂ $k_{84} = 2.7 \times 10^{-11}$	61	
	-	_	-	85	$CO + H_3^+ \rightarrow HCO$		61	
				86	$HCO^+ + C \rightarrow CO$	$+ 0.01$ R86 $= 1.1 \times 10^{-6}$	28	



							01 #0102		-
		14	H-	+ H -	\rightarrow H + H + e	88	$H_2 + He^+ \rightarrow He + H_2^+$	$k_{88} = 7.2 \times 10^{-15}$	63
	-		- 1	36	$CH + H_2 -$	89	$H_2 + He^+ \rightarrow He + H + H^+$	$k_{89} = 3.7 \times 10^{-14} \exp\left(\frac{35}{T}\right)$	63
Table	B1. 1			37	$CH + C \rightarrow$	90	$CH + H^+ \rightarrow CH^+ + H$	$k_{90} = 1.9 \times 10^{-9}$	28
	_			38	CH + C +	91 92	$CH_2 + H^+ \rightarrow CH_2^+ + H$ $CH_2 - H_2^+ \rightarrow U^+ + H_2$	$k_{91} = 1.4 \times 10^{-9}$	28 28
No.	Rea					93	$C_1 + 1e \rightarrow C_1 + C_2 + 1e - H_2$	$\frac{92}{93} = 6 \times 1^{-9}$	28
1	H +			39 40	$CH_2 + O -$	94	$OH + H^+ \rightarrow OH^+ + H$	$k_{94} = 2.1 \times 10^{-3}$	28
-				41	$CH_2 + O - CH_2 + O - O$	95	$\rm OH + He^+ \rightarrow O^+ + He + H$	$k_{95} = 1.1 \times 10^{-9}$	28
				42	$C_2 + O \rightarrow$	96	$H_2O + H^+ \rightarrow H_2O^+ + H$	$k_{96} = 6.9 \times 10^{-9}$	64
						97 98	$H_2O + He^+ \rightarrow OH + He + H^+$ $H_2O + He^+ \rightarrow OH^+ + He + H$	$k_{97} = 2.04 \times 10^{-10}$ $k_{98} = 2.86 \times 10^{-10}$	65 65
2	н-	15	H-	43	0.1.11	99	$H_2O + He^+ \rightarrow H_2O^+ + He$	$k_{99} = 6.05 \times 10^{-11}$	65
-		16	He		$O + H_2 \rightarrow$	100	$O_2 + H^+ \rightarrow O_2^+ + H$	$k_{100} = 2.0 \times 10^{-9}$	64
3	H +			44	$OH + H \rightarrow$	101	$O_2 + He^+ \rightarrow O_2^+ + He$	$k_{101} = 3.3 \times 10^{-11}$	66
				45	$OH + H_2 -$	102	$O_2 + He^+ \rightarrow O^+ + O + He$	$k_{102} = 1.1 \times 10^{-9}$	66
4	H +			46 47	$OH + C \rightarrow$ $OH + O \rightarrow$	103	$O_2^+ + C \rightarrow O_2 + C^+$	$k_{103} = 5.2 \times 10^{-11}$	28
5 6	H^{-} H_{2}^{+}				01+0-	104	$\rm CO + He^+ \rightarrow C^+ + O + He$	$k_{104} = 1.4 \times 10^{-9} \left(\frac{T}{300}\right)^{-0.5}$	67
	112			48	OH + OH	105	$CO + He^+ \rightarrow C + O^+ + He$	$k_{105} = 1.4 \times 10^{-16} \left(\frac{T}{300}\right)^{-0.5}$ $k_{105} = 7.5 \times 10^{-10}$	67
7	H_2 ·			49	$H_2O + H -$	106	$CO^+ + H \rightarrow CO + H^+$	N106 - 1.5 × 10	68
		17		49 50	$H_2O + H \rightarrow$ $O_2 + H \rightarrow$	107	$C^- + H^+ \rightarrow C + H$	$k_{107} = 2.3 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.5}$	28
		17	He	51	$O_2 + H \rightarrow$ $O_2 + H_2 -$	108	$O^- + H^+ \rightarrow O + H$	$k_{108} = 2.3 \times 10^{-1} \left[\frac{1}{1000} \right]$	28
						109	$\mathrm{He^+} + \mathrm{H^-} \rightarrow \mathrm{He} + \mathrm{H}$	$k_{109} = 2.32 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.52} \exp\left(\frac{T}{22400}\right)$	69
				52	$O_2 + C \rightarrow$	110	$H_3^+ + e^- \rightarrow H_2 + H$	$k_{110} = 2.34 \times 10^{-6} \left(\frac{1}{300}\right)$	70
						111	$H_3^+ + e^- \rightarrow H + H + H$	$k_{111} = 4.36 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.52}$	70
				53	$CO + H \rightarrow$	112	$CH^+ + e^- \rightarrow C + H$	$k_{112} = 7.0 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.5}$	71
8	H_2 .	18	He	54	$H_2^+ + H_2 -$	113	$CH_2^+ + e^- \rightarrow CH + H$	$k_{113} = 1.6 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.6}$	72
9	H_2 .	19	He	55	$H_3^+ + H \rightarrow$	114	$CH_2^+ + e^- \rightarrow C + H + H$	$k_{114} = 4.03 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.6}$	72
				56 57	$C + H_2^+ \rightarrow C + H_3^+ \rightarrow$	115	$CH_2^+ + e^- \rightarrow C + H_2$	$k_{115} = 7.68 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.6}$	72
		20	C^+	58	$C^{+} H_{2}^{-}$	116	$CH_3^+ + e^- \rightarrow CH_2 + H$	$k_{116} = 7.75 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.5}$	73
				59	$CH^{+} + H$ -	117	$CH_3^+ + e^- \rightarrow CH + H_2$	$k_{117} = 1.95 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.5}$	73
10	H2 -			60	$CH^+ + H_2$	118	$CH_3^+ + e^- \rightarrow CH + H + H$	$k_{118} = 2.0 \times 10^{-7} \left(\frac{T}{300} \right)^{-0.4}$	28
		21	0+	61 62	$CH^+ + O - CH_0 + H^+$	119	$OH^+ + e^- \rightarrow O + H$	$k_{119} = 6.3 \times 10^{-9} \left(\frac{T}{300} \right)^{-0.48}$	74
				63	$CH_2 + H^+$ $CH_2^+ + H^-$	120	$H_2O^+ + e^- \rightarrow O + H + H$	$k_{120} = 3.05 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.5}$ $k_{120} = 3.05 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.5}$	75
11	H +	22	C+	64	$CH_{2}^{+} + H_{2}$	120	$H_2O^+ + e^- \rightarrow O + H_2$ $H_2O^+ + e^- \rightarrow O + H_2$	$k_{121} = 3.9 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.5}$	75
		23	0+	65	$CH_2^+ + O$				
		24	0+	66	$CH_3^+ + H -$	122	$H_2O^+ + e^- \rightarrow OH + H$	$k_{122} = 8.6 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.5}$	75
		25	0+	67	$CH_{3}^{+} + O$	123	$H_3O^+ + e^- \rightarrow H + H_2O$	$k_{123} = 1.08 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.5}$	76
		0.0		68	$C_2 + O^+ - O^+$	124	$H_3O^+ + e^- \rightarrow OH + H_2$	$k_{124} = 6.02 \times 10^{-8} \left(\frac{4}{300}\right)$	76
		26	0+	69 70	$O^+ + H_2 - O + H_2^+ \rightarrow$	125	$\rm H_{3}O^{+} + e^{-} \rightarrow OH + H + H$	$k_{125} = 2.58 \times 10^{-7} \left(\frac{4}{300}\right)_{0.5}$	76
		07	C+	71	$O + H_2^+ \rightarrow O + H_3^+ \rightarrow$	126	$\rm H_3O^+ + e^- \rightarrow O + H + H_2$	$k_{126} = 5.6 \times 10^{-9} \left(\frac{4}{300} \right)$	76
12	H^+	27 28	C+	72	$OH + H_3^+$	127	$O_2^+ + e^- \rightarrow O + O$	$k_{127} = 1.95 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.7}$	77
		28 29	C+	73	$OH + C^+$	128	$\rm CO^+ + e^- \rightarrow \rm C + \rm O$	$k_{128} = 2.75 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.55}$	78
		20	01	74 75	$OH^{+} + H_{2}$ $H_{2}O^{+} + H$	129	$\rm HCO^+ + e^- \rightarrow \rm CO + \rm H$	$k_{129} = 2.76 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.64}$	79
				76	$H_2O + H_3^+$	130	$HCO^+ + e^- \rightarrow OH + C$	$k_{130} = 2.4 \times 10^{-8} \left(\frac{T}{200}\right)^{-0.64}$	79
13	н-	30	H ₂	77	$H_2O + C^+$	131	$\rm HOC^+ + e^- \rightarrow \rm CO + \rm H$	$k_{131} = 1.1 \times 10^{-7} \left(\frac{T}{300}\right)^{-1.0}$ $k_{132} = 1.0 \times 10^{-9}$	28
				78	$H_2O + C^+$	132	$\rm H^- + C \rightarrow CH + e^-$	8132 - 1.0 X 10	28
		31	он	79	$H_3O^+ + C$ $O_2 + C^+ -$	133	$\rm H^- + O \rightarrow OH + e^-$	$k_{133} = 1.0 \times 10^{-9}$	28
		32	но	80 81	$O_2 + C^+ = O_2 + O_2 + C^+ = O_2 + O_2 $	134	$H^- + OH \rightarrow H_2O + e^-$ $C^- + H \rightarrow CH + e^-$	$k_{134} = 1.0 \times 10^{-10}$ $k_{135} = 5.0 \times 10^{-10}$	28
		33	но	82	$O_2 + CH_2^+$	135 136	$C^- + H \rightarrow CH + e^-$ $C^- + H_2 \rightarrow CH_2 + e^-$	$k_{135} = 5.0 \times 10^{-13}$ $k_{136} = 1.0 \times 10^{-13}$	28 28
		34	C+	83	$O_2^+ + C \rightarrow$	137	$C^- + O \rightarrow CO + e^-$	$k_{137} = 5.0 \times 10^{-10}$	28
		35	CH	84	$CO + H_3^+$	138	$\rm O^- + H \rightarrow OH + e^-$	$k_{138} = 5.0 \times 10^{-10}$	28
			-	85	$CO + H_3$	139	$O^- + H_2 \rightarrow H_2O + e^-$	$k_{139} = 7.0 \times 10^{-10}$	28
				86	$HCO^+ + C$	140	$O^- + C \rightarrow CO + e^-$	$k_{140} = 5.0 \times 10^{-10}$	28



14 H		- 1						6		- 1	
Table BI. So. Res Description Cliption Cliption Cliption Cliption Cliption Cliption Cliption Cliption So. Feature Fea			14	H^{-}	+H -	H + H + e	88	$H_2 + He^+ \rightarrow He + H_2^+$	$k_{88} = 7.2 \times 10^{-15}$	63	
Table BI. So. Fig. 2					36	$CH + H_2 -$	89	$H_2 + He^+ \rightarrow He + H^+ H^+$	$k_{89} = 3.7 \times 10^{-14} \exp \left(\frac{35}{T}\right)$	63	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Table	B1.			37		90		$k_{90} = 1.9 \times 10^{-9}$	28 Zanna biz Anton	omie Heidelterg
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	1000				38	$CH + C \rightarrow$	91	$CH_2 + H^+ \rightarrow CH_2^+ + H$	$k_{91} = 1.4 \times 10^{-9}$	ARITIAT	sw
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	No.	Rea						$O_1 = H_1 \rightarrow J_2 \rightarrow H_2$			
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$		_			39	C I -					
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	1	н+								-	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$						-					
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$					42	$C_2 + O \rightarrow$	97	$H_2O + He^+ \rightarrow OH + He + H^+$	$k_{97} = 2.04 \times 10^{-10}$	65	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			15	H^{-}				U O + U-+ - OU+ + U- + U	2 n ee - 10-10	0E	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	2	H^{-}			43	$O + H_2 \rightarrow$		142 $C + e^- \rightarrow C^- + \gamma$	$k_{142} = 2.25 \times 10^{-15}$		81
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	_		16	He	44	$OH + H \rightarrow$		143 $C + H \rightarrow CH + \gamma$	$k_{143} = 1.0 \times 10^{-17}$		82
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	3	н+			45	$OH + H_2 =$	10		$k_{144} = 1.0 \times 10^{-17}$		82
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	4	H+					10		$k_{145} = 4.36 \times 10^{-18} \left(\frac{T}{300}\right)^{0.05} \exp\left(-\frac{161.3}{T}\right)$		83
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	-							146 $C + O \rightarrow CO + \gamma$	$\kappa_{146} = 2.1 \times 10^{-10}$	$T \leq 300 \text{ K}$	84
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$									$= 3.09 \times 10^{-17} \left(\frac{T}{300}\right)^{0.33} \exp \left(-\frac{1629}{T}\right)$	$T > 300 { m K}$	85
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$		1			48	OH + OH -		147 $C^+ + H \rightarrow CH^+ + \gamma$	$k_{147} = 4.46 \times 10^{-16} T^{-0.5} \exp\left(-\frac{4.93}{m^{2}/3}\right)$		86
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	7	H_2 ·						148 $C^+ + H_2 \rightarrow CH_2^+ + \gamma$	$k_{148} = 4.0 \times 10^{-16} \left(\frac{T}{200}\right)^{-0.2}$		87
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			177	U.			10	6	$k_{149} = 2.5 \times 10^{-18}$	$T \leq 300 \text{ K}$	
$ \begin{array}{c} 52 O_2 + C - \\ 53 CO + H - \\ 54 H_1^5 + H_2 - \\ 9 H_2 \\ 9 H_2 \\ 9 H_2 \\ 9 H_2 \\ 10 H_2 \\ 20 C^+ \\ 55 C^+ H_3^- + H \\ 11 13 O^+ H - H_2 O + \gamma \\ 55 C^+ H_3^- + H \\ 11 13 O^+ H - H_2 O + \gamma \\ 11 13 O^+ H - H_2 O + \gamma \\ 11 13 O^+ H - H_2 O + \gamma \\ 11 13 O^+ H - H_2 O + \gamma \\ 11 13 O^+ H - H_2 O + \gamma \\ 11 13 O^+ H - H_2 O + \gamma \\ 11 13 O^+ H - H_2 O + \gamma \\ 11 13 O^+ H - H_2 O + \gamma \\ 11 13 O^+ H - H_2 O + \gamma \\ 11 13 O^+ H - H_2 O + \gamma \\ 11 15 O^+ H - H_2 O + \gamma \\ 11 15 O^+ H - H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H + H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 11 15 H^+ H^+ H_2 O + \gamma \\ 12 15 O^+ H^+ H^+ H_2 O + \gamma \\ 12 15 O^+ H^+ H^+ H_2 O + \gamma \\ 12 15 O^+ H^+ H^+ H_2 O + \gamma \\ 12 H^+ H^+ H^+ H_2 O + \gamma \\ 12 H^+ H^+ H^+ H^+ H^+ H^+ H^+ H^+ H^+ H^+$			17	He		-	10		$= 3.14 \times 10^{-18} \left(\frac{T}{T}\right)^{-0.15} \exp\left(\frac{68}{5}\right)$		
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$							10	150 $O + e^- \rightarrow O^- + \gamma$	$k_{150} = 1.5 \times 10^{-10}$		28
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$					52	$O_2 + C \rightarrow$			$k_{151} = 9.9 \times 10^{-19} \left(\frac{T}{T}\right)^{-0.38}$		
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$									$h_{131} = 4.0 \times 10^{-20} \begin{pmatrix} 300 \\ T \end{pmatrix}^{1.58}$		
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$					53	$\rm CO + H \rightarrow$	1.1		$\kappa_{152} = 4.9 \times 10^{-10} \left(\frac{300}{300}\right)$		
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			10	He	54	$H_2^+ + H_2 -$			$k_{153} = 5.26 \times 10^{-16} \left(\frac{1}{300}\right) \exp\left(-\frac{30}{T}\right)$		88
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	8	H_2 ·			55	$H_3^+ + H \rightarrow$		$154 H + H + H \rightarrow H_2 + H$	$k_{154} = 1.32 \times 10^{-32} \left(\frac{1}{300} \right)$	$T \leq 300 \text{ K}$	89
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	9	H_2 ·	19	ne	56	$C + H_2^+ \rightarrow$			$= 1.32 \times 10^{-32} \left(\frac{T}{300} \right)^{-1.0}$	$T > 300 { m K}$	90
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			20	C+	57	$C + H_3^+ \rightarrow$			$\kappa_{155} = 2.8 \times 10^{-5.1}$		
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			20	0	58		11	156 $H + H + He \rightarrow H_2 + He$	$k_{156} = 6.9 \times 10^{-32} T^{-0.4}$		92
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	10						11	157 $C + C + M \rightarrow C_2 + M$	$k_{157} = 5.99 \times 10^{-33} \left(\frac{T}{5000}\right)^{-1.5}$	$T \leqslant 5000 \text{ K}$	93
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	10	H2 ·					11		$= 5.99 \times 10^{-33} \left(\frac{1}{5000} \right) \exp \left(\frac{3235}{T} \right)$	$T > 5000 { m K}$	94
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			21	0+			11	158 $C + O + M \rightarrow CO + M$	$k_{158} = 6.16 \times 10^{-29} \left(\frac{T}{200}\right)^{-3.08}$	$T \leq 2000 \text{ K}$	35
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$									$-2.14 \times 10^{-29} \left(\frac{T}{T}\right)^{-3.08} \exp\left(\frac{2114}{T}\right)$	-	
$12 H^{+} \begin{array}{c} 23 0 + \ 65 CH_{2}^{+} + 0 \\ 24 0^{+} \\ 66 CH_{3}^{+} + H \\ 25 0 - \ 67 CH_{3}^{+} + 0 \\ 66 CH_{3}^{+} + H \\ 25 0 - \ 67 CH_{3}^{+} + 0 \\ 66 CH_{3}^{+} + H \\ 25 0 - \ 67 CH_{3}^{+} + 0 \\ 66 CH_{3}^{+} + H \\ 26 0 - \ 69 0^{+} + H_{2} \\ 70 0 - H_{2}^{+} \\ 70 0 - H_{3}^{+} \\ 70 0 - H_{3}^{+} \\ 72 CH 71 0 + H_{3}^{+} \\ 73 OH + C^{+} \\ 29 CH 74 OH^{+} + H_{2} \\ 75 H_{2}O^{+} + H \\ 75 H_{2}O^{+} + C^{+} \\ 78 H_{2}O^{+} + C^{+} \\ 71 H^{+} + O^{+} + O^{+} + O^{+} \\ 75 H_{2}O^{+} + C^{+} \\ 75 H_{2}O^{+} + C^{+} \\ 75 H_{2}O^{+} + C^{+} \\ 78 H_{2$	11	H +	99	C.		-		159 $C^+ + O + M \rightarrow CO^+ + M$		1 × 2000 R	
$ \begin{array}{c} 24 & 0^{+} & 66 & CH_{3}^{+} + H \\ 25 & 0^{-} & 67 & CH_{3}^{+} + 0 \\ 68 & C_{2} + 0^{+} \\ 68 & C_{2} + 0^{+} \\ 68 & C_{2} + 0^{+} \\ 70 & 0 + H_{2} \\ 70 & 0 + H_{2} \\ 71 & 0 + H_{3} \\ 71 & 0 + H_{3} \\ 72 & C_{4} \\ 71 & 0 + H_{3} \\ 71 & 10 + H_{3} \\ 71 & 10 + H_{3} \\ 71 & 10 + H_{3} \\ 71 & H_{2}O + C^{+} \\ 73 & 0H + C^{+} \\ 73 & 0H + C^{+} \\ 73 & 10H + C^{+} \\ 73 & H_{2}O + C^{+} \\ 71 & H_{2}O + C^{+} \\ 72 & H_{2}O + C^{+} \\ 73 & H_{2}O + C^{+} \\ 73 & H_{2}O + C^{+} \\ 71 & H_{2}O + C^{+} \\ 71 & H_{2}O + C^{+} \\ 72 & H_{2}O + C^{+} \\ 73 & H^{-} O \rightarrow O + H \\ 74 & H^{-} O \rightarrow O + H^{-} \\ 75 & H_{2}O + C^{+} \\ 71 & H^{-} O \rightarrow O + H^{-} \\ 71 & H^{-} O \rightarrow O + $						-	12				
$12 H^{+} \begin{array}{c} 12 0^{+} 0^{+} 0^{+} 0^{+} 0^{+} 0^{+} 0^{+} 0^{+} 1^{2} \\ 68 C_{2} + O^{+} 1^{2} \\ 70 O^{+} + H_{2} - \\ 70 O^{+} + H_{3} - \\ 72 O^{+} 1^{2} 1^{2} \\ 165 H^{+} H(s) \rightarrow H_{2} \\ 165 H^{+} H(s) \rightarrow H_{2} \\ 165 H^{+} H(s) \rightarrow H_{2} \\ 12 \\ \end{array} \begin{array}{c} 166 H^{+} H(s) \rightarrow H_{2} \\ H^{+} \\ 28 C^{+} \\ 73 OH + C^{+} \\ 29 C^{+} 74 OH^{+} + H_{2} \\ 75 H_{2}O^{+} + H \\ 129 C^{+} + e^{-} \rightarrow OH + C \\ 75 H_{2}O^{+} + H \\ 129 H^{+}O^{+} + e^{-} \rightarrow OH + C \\ 81_{129} = 2.76 \times 10^{-7} \left(\frac{7}{30}\right)^{-0.64} \\ 79 \\ 76 H_{2}O + H^{+} \\ 78 H_{2}O + C^{+} \\ 78 H_{2}O + C^{+} \\ 78 H_{2}O + C^{+} \\ 131 H^{-}C^{+} + e^{-} \rightarrow OH + C \\ 81_{130} = 2.4 \times 10^{-8} \left(\frac{7}{300}\right)^{-1.0} \\ 28 \\ 131 OH 80 O_{2} + C^{+} \\ 79 H_{3}O^{+} + C \\ 132 H^{-} + O \rightarrow OH + e^{-} \\ 81_{132} = 1.0 \times 10^{-9} \\ 28 \\ 131 OH 80 O_{2} + C^{+} \\ 133 H^{-} + O \rightarrow OH + e^{-} \\ 81_{133} = 1.0 \times 10^{-9} \\ 28 \\ 14 C^{+} + 83 O_{2}^{+} + C \\ 33 H^{-} + O \rightarrow OH + e^{-} \\ 81_{33} C^{-} + H \rightarrow OH + e^{-} \\ 81_{33} = 5.0 \times 10^{-10} \\ 28 \\ 34 C^{+} 83 O_{2}^{+} + C \\ 35 C^{+} H_{3} 138 O^{-} + H \rightarrow OH + e^{-} \\ 81_{33} C^{-} + H \rightarrow OH + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} = 5.0 \times 10^{-10} \\ 28 \\ 85 CO + H_{3}^{+} 138 O^{-} + H \rightarrow OH + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-} \\ 81_{33} F^{-} + O \rightarrow OC + e^{-}$							12		$k_{161} = 4.33 \times 10^{-32} \left(\frac{T}{T}\right)^{-1.0}$		43
$ \begin{array}{c} 12 \mathrm{H}^{+} \\ 12 \mathrm{H}^{+} \\ 13 \mathrm{H}^{-} \\ \begin{array}{c} 13 \mathrm{H}^{-} \\ 13 \mathrm{H}^{-} \\ \begin{array}{c} 13 \mathrm{H}^{-} \\ 13 \mathrm{H}^{-} \\ \begin{array}{c} 26 \mathrm{O} \\ \mathrm{O} \\ \mathrm{O} \\ \mathrm{H} \\ \mathrm{H}^{+} \\ \mathrm{H}^{+} \\ \end{array} \begin{array}{c} 26 \mathrm{O} \\ \mathrm{O} \\ \mathrm{O} \\ \mathrm{H} \\ \mathrm{H}^{+} \\ \mathrm{H}^{+} \\ \mathrm{H}^{+} \\ \end{array} \begin{array}{c} 26 \mathrm{O} \\ \mathrm{O} \\ \mathrm{O} \\ \mathrm{H} \\ \mathrm{H}^{+} \\ \mathrm{H}^{+} \\ \end{array} \begin{array}{c} 27 \mathrm{C} \\ \mathrm{C} \\ \mathrm{H} \\ \mathrm{H}^{+} \\ \mathrm{H}^$			25	0+	67		12		(300)		
$12 H^{+} = \begin{bmatrix} 27 C \\ 71 O \\ +H_{2}^{-} \\ 28 C^{+} \\ 72 OH \\ +H_{3}^{+} \\ 29 C \\ +74 OH \\ +H_{4} \\ 129 HCO^{+} \\ +e^{-} \\ +CO \\ +H \\ +H(s) \\ \rightarrow H_{2} \\ +D(02 \\ T \\ +S \\ +S \\ +O \\ +O \\ +S \\ +S \\ +O \\ +O$					68		12	•	$\kappa_{162} = 2.36 \times 10^{-1.0}$		
$ \begin{array}{c} 12 \mathrm{H}^{+} \\ 12 \mathrm{H}^{+} \\ \begin{array}{c} 27 \mathrm{C}^{+} \\ 28 \mathrm{C}^{+} \\ 72 \mathrm{OH} + \mathrm{H}_{3}^{+} \\ 29 \mathrm{C}^{+} \\ 73 \mathrm{OH} + \mathrm{C}^{+} \\ 29 \mathrm{C}^{+} \\ 73 \mathrm{OH} + \mathrm{H}_{4} \\ 29 \mathrm{C}^{+} \\ 73 \mathrm{OH} + \mathrm{H}_{4} \\ 75 \mathrm{H}_{2}\mathrm{O}^{+} + \mathrm{H} \\ 75 \mathrm{H}_{2}\mathrm{O}^{+} + \mathrm{H} \\ 75 \mathrm{H}_{2}\mathrm{O}^{+} + \mathrm{H} \\ 77 \mathrm{H}_{2}\mathrm{O} + \mathrm{H}_{3}^{+} \\ 77 \mathrm{H}_{2}\mathrm{O} + \mathrm{C}^{+} \\ 77 \mathrm{H}_{2}\mathrm{O} + \mathrm{C}^{+} \\ 78 \mathrm{H}_{2}\mathrm{O} + \mathrm{C}^{+} \\ 8 \mathrm{H}^{-} \\ 73 \mathrm{OH} + \mathrm{C}^{+} - \\ 74 \mathrm{OH}^{+} + \mathrm{H}_{2} \\ 75 \mathrm{H}_{2}\mathrm{O}^{+} + \mathrm{H} \\ 76 \mathrm{H}_{2}\mathrm{O} + \mathrm{H}_{3}^{+} \\ 77 \mathrm{H}_{2}\mathrm{O} + \mathrm{C}^{+} \\ 78 \mathrm{H}_{2}\mathrm{O} + \mathrm{C}^{+} \\ 78 \mathrm{H}_{2}\mathrm{O} + \mathrm{C}^{+} \\ 79 \mathrm{H}_{3}\mathrm{O}^{+} + \mathrm{C} \\ 78 \mathrm{H}_{2}\mathrm{O} + \mathrm{C}^{+} \\ 79 \mathrm{H}_{3}\mathrm{O}^{+} + \mathrm{C} \\ 79 \mathrm{H}_{3}\mathrm{O} + \mathrm{C}^{+} \\ 79 \mathrm{H}_{3}\mathrm{O} + \mathrm{C}^{+} \\ 131 \mathrm{HOC}^{+} + \mathrm{e}^{-} \\ 79 \mathrm{H}_{3}\mathrm{O} + \mathrm{H}^{-} \\ 73 \mathrm{H}^{-} \\ 79 \mathrm{H}_{3}\mathrm{O} + \mathrm{C}^{+} \\ 79 \mathrm{H}_{3}\mathrm{O} + \mathrm{C}^{+} \\ 131 \mathrm{HOC}^{+} + \mathrm{e}^{-} \\ 79 \mathrm{H}_{3}\mathrm{O} + \mathrm{C}^{+} \\ 132 \mathrm{H}^{-} + \mathrm{C} \rightarrow \mathrm{CO} + \mathrm{H} \\ 79 \mathrm{H}_{3}\mathrm{O} + \mathrm{C}^{+} \\ 132 \mathrm{H}^{-} + \mathrm{C} \rightarrow \mathrm{CO} + \mathrm{H} \\ 80 \mathrm{O}_{2} + \mathrm{C}^{+} \\ 133 \mathrm{HO} + \mathrm{H}_{2} \\ 31 \mathrm{OH} \\ 80 \mathrm{O}_{2} + \mathrm{C}^{+} \\ 133 \mathrm{H}^{-} + \mathrm{OH} \rightarrow \mathrm{H}_{2}\mathrm{O} \\ 133 \mathrm{H}^{-} + \mathrm{OH} \rightarrow \mathrm{H}_{2}\mathrm{O} \\ 133 \mathrm{H}^{-} + \mathrm{OH} \rightarrow \mathrm{H}_{2}\mathrm{O} \\ 133 \mathrm{H}^{-} + \mathrm{OH} \rightarrow \mathrm{CH}_{4} \\ 34 \mathrm{C} + \\ 83 \mathrm{O}_{2}^{+} + \mathrm{C} \\ 136 \mathrm{C}^{-} + \mathrm{H}_{2} \rightarrow \mathrm{CH}_{2} + \mathrm{e}^{-} \\ 137 \mathrm{C}^{-} + \mathrm{O} \rightarrow \mathrm{CO} + \mathrm{e}^{-} \\ 8138 \mathrm{E} 1.0 \times 10^{-13} \\ 138 \mathrm{O}^{-} + \mathrm{H} \rightarrow \mathrm{OH} + \mathrm{e}^{-} \\ 8138 \mathrm{E} 0 \times 10^{-10} \\ 28 \\ 86 \mathrm{HO}^{+} + \mathrm{C} \\ 140 \mathrm{O}^{-} + \mathrm{C} \rightarrow \mathrm{CO} + \mathrm{e}^{-} \\ 8139 \mathrm{O} \times 10^{-10} \\ 28 \\ 86 \mathrm{HO}^{+} + \mathrm{C} \\ 140 \mathrm{O}^{-} + \mathrm{C} \rightarrow \mathrm{CO} + \mathrm{e}^{-} \\ 8139 \mathrm{O} \times 10^{-10} \\ 28 \\ 86 \mathrm{HO}^{+} + \mathrm{C} \\ 140 \mathrm{O}^{-} + \mathrm{C} \rightarrow \mathrm{CO} + \mathrm{e}^{-} \\ 8139 \mathrm{O} \times 10^{-10} \\ 28 \\ 86 \mathrm{HO}^{-} + \mathrm{C} \\ 86 \mathrm{HO}^{-} + \mathrm{C} \\ 86 \mathrm{HO}^{-} + \mathrm{C} \\ 140 \mathrm{O}^{-} + \mathrm{C} \rightarrow \mathrm{CO} + \mathrm{C}^{-} \\ 8139 \mathrm{O} \times $			26	0+	69	$O^+ + H_2 -$	12		$k_{163} = 9.2 \times 10^{-34} \left(\frac{1}{300} \right)$		
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$						-		$164 O + CH \rightarrow HCO^+ + e^-$	$k_{164} = 2.0 \times 10^{-11} \left(\frac{T}{300}\right)^{-11}$		95
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			27	C +				165 $H + H(s) \rightarrow H_2$	$k_{165} = 3.0 \times 10^{-18} T^{0.5} f_{\Lambda} [1.0 + 0.04(T + T_d)^0]$	$f_A = \left[1.0 + 10^4 \exp\left(-\frac{600}{T_A}\right)\right]^{-1}$	96
$13 H^{-} \begin{bmatrix} 29 & C + & 74 & OH^{+} + H_{2} & 129 & HCO^{+} + e^{-} \rightarrow CO + H & k_{129} = 2.76 \times 10^{-7} \begin{pmatrix} T \\ 300 \end{pmatrix}^{-0.64} & 79 \\ \hline 75 & H_{2}O^{+} + H & 130 & HCO^{+} + e^{-} \rightarrow OH + C & k_{130} = 2.4 \times 10^{-8} \left(\frac{T}{300} \right)^{-0.64} & 79 \\ \hline 76 & H_{2}O + H_{3}^{+} & 130 & HCO^{+} + e^{-} \rightarrow OH + C & k_{130} = 2.4 \times 10^{-8} \left(\frac{T}{300} \right)^{-1.0} & 28 \\ \hline 77 & H_{2}O + C^{+} & 131 & HOC^{+} + e^{-} \rightarrow CO + H & k_{131} = 1.1 \times 10^{-7} \left(\frac{T}{300} \right)^{-1.0} & 28 \\ \hline 79 & H_{3}O^{+} + C & 132 & H^{-} + C \rightarrow OH + e^{-} & k_{132} = 1.0 \times 10^{-9} & 28 \\ \hline 79 & H_{3}O^{+} + C & 133 & H^{-} + O \rightarrow OH + e^{-} & k_{133} = 1.0 \times 10^{-9} & 28 \\ \hline 31 & OH & 80 & O_{2} + C^{+} & 134 & H^{-} + OH \rightarrow H_{2}O + e^{-} & k_{133} = 1.0 \times 10^{-10} & 28 \\ \hline 32 & HO & 81 & O_{2} + C^{+} & 135 & C^{-} + H \rightarrow CH + e^{-} & k_{135} = 5.0 \times 10^{-10} & 28 \\ \hline 33 & HO & 82 & O_{2} + CH_{2}^{+} & 136 & C^{-} + H_{2} \rightarrow CH_{2} + e^{-} & k_{136} = 1.0 \times 10^{-13} & 28 \\ \hline 34 & C + & 83 & O_{2}^{+} + C & - & 137 & C^{-} + O \rightarrow CO + e^{-} & k_{138} = 5.0 \times 10^{-10} & 28 \\ \hline 35 & CH & 84 & CO + H_{3}^{+} & 138 & O^{-} + H_{2} \rightarrow H_{2}O + e^{-} & k_{139} = 7.0 \times 10^{-10} & 28 \\ \hline 86 & HCO^{+} + C & 140 & O^{-} + C \rightarrow CO + e^{-} & k_{139} = 7.0 \times 10^{-10} & 28 \\ \hline \end{bmatrix}$	12	H^+	28	C^+					$+ 0.002 T + 8 \times 10^{-6} T^{2}]^{-1}$		
$ \begin{array}{c} 13 \mathrm{H}^{-} \\ \begin{array}{c} 30 \mathrm{H}_{2} \\ \begin{array}{c} 30 \mathrm{H}_{2} \\ 30 \mathrm{H}_{2} \\ 31 \mathrm{OH} \\ 31 \mathrm{OH} \\ 32 \mathrm{H}^{-} \\ \end{array} \\ \begin{array}{c} 30 \mathrm{H}_{2} \\ 31 \mathrm{OH} \\ 32 \mathrm{H}^{-} \\ 32 \mathrm{H}^{-} \\ 33 \mathrm{H}^{-} \\ 32 \mathrm{H}^{-} \\ 31 \mathrm{OH} \\ 31 \mathrm{OH} \\ 32 \mathrm{H}^{-} \\ 32 \mathrm{H}^{-} \\ 32 \mathrm{H}^{-} \\ 32 \mathrm{H}^{-} \\ 33 \mathrm{H}^{-} \\ 33 \mathrm{H}^{-} \\ 32 \mathrm{H}^{-} \\ 33 \mathrm{H}^{-} \\ 32 \mathrm{H}^{-} \\ 33 \mathrm{H}^{-} \\ 33 \mathrm{H}^{-} \\ 34 \mathrm{C}^{+} \\ 33 \mathrm{H}^{-} \\ 35 \mathrm{CH} \\ 34 \mathrm{C}^{+} \\ 35 \mathrm{CH} \\ 35 \mathrm{CH} \\ 35 \mathrm{CH} \\ 35 \mathrm{CH} \\ 36 \mathrm{H}^{-} \\ 36 \mathrm{C}^{-} \\ 36 \mathrm{H}^{-} \\ 36 \mathrm{C}^{-} \\ 37 \mathrm{H}^{-} \\ 37 \mathrm{C}^{-} \\ 38 \mathrm{C}^{-} \\ 39 \mathrm{C}^{-} \\ 38 \mathrm{C}^{-} \\ 39 \mathrm{C}^{-} \\ 38 \mathrm{C}^{-} \\ 3$			29	C +					~ > m < = 0.64		
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$							129	$HCO^+ + e^- \rightarrow CO + H$	$k_{129} = 2.76 \times 10^{-7} \left(\frac{1}{300}\right)^{-0.04}$	79	
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$			80				130	$\rm HCO^+ + e^- \rightarrow OH + C$	$k_{130} = 2.4 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.64}$	79	
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	13	н-	30	H ₂			131	$\rm HOC^+ + e^- \rightarrow \rm CO + \rm H$	$k_{131} = 1.1 \times 10^{-7} \left(\frac{T}{300}\right)^{-1.0}$	28	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$									$k_{132} = 1.0 \times 10^{-5}$		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			21	OP					$k_{133} = 1.0 \times 10^{-9}$	28	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$									$k_{134} = 1.0 \times 10^{-10}$		
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$									$k_{135} = 5.0 \times 10^{-10}$		
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$									$\kappa_{136} = 1.0 \times 10^{-10}$		
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$											
$= 86 \text{ HCO}^+ + C 140 \text{ O}^- + C \rightarrow CO + e^- \qquad k_{140} = 5.0 \times 10^{-10} \qquad 28$											
87 $HCO^+ + H_2O \rightarrow CO + H_3O^+$ $k_{87} = 2.5 \times 10^{-9}$ 62						$HCO^+ + C$	140	$O^- + C \rightarrow CO + e^-$	$k_{140} = 5.0 \times 10^{-10}$		
	_	-	-	-	87	$HCO^+ + H_2$	$_2O \rightarrow CO$		62		



	14 H ⁻	$+ H \rightarrow H + H +$	e 88	$H_2 + He^+ \rightarrow He + H_2^+$	$k_{88} = 7.2 \times 10^{-15}$	63
		36 CH + H	, 89	$H_2 + He^+ \rightarrow He + H^+ H^+$	$k_{89} = 3.7 \times 10^{-14} \exp \left(\frac{35}{T}\right)$	63
Table B1.		37 CH + C		$CH + H^+ \rightarrow CH^+ + H$	$k_{90} = 1.9 \times 10^{-9}$	28
THOIC DI		38 CH + C	91	$CH_2 + H^+ \rightarrow CH_2^+ + H$	$k_{91} = 1.4 \times 10^{-9}$	28
No. Rea			92	$C_{2} = H_{1} \xrightarrow{\tau} \rightarrow J_{2} \xrightarrow{\bullet} Ie = H_{2}$		28
100 100		39 C	- 93			28
1 H+	_	$40 CH_2 + C$) - 94	$OH + H^+ \rightarrow OH^+ + H$	$k_{94} = 2.1 \times 10^{-3}$	28
	_	41 $CH_2 + C$)_ 95	$OH + He^+ \rightarrow O^+ + He + H$	$k_{95} = 1.1 \times 10^{-9}$	28
	_			$H_2O + H^+ \rightarrow H_2O^+ + H$	$k_{96} = 6.9 \times 10^{-9}$	64
	_	$42 - C_2 + O_2$	→ 97	$H_2O + He^+ \rightarrow OH + He + H^+$	$k_{97} = 2.04 \times 10^{-10}$	65
	15 H-		98	U.O. 1 U-+ . OU+ 1 U- 1 U	h _ 0.66 v 10-10	05

	15 H-	20			pp 10 pr	
able	B2. List of photochemical	reactions included in our che	emical mode	el		81 82
		-			0×10^{-17}	82
No.	Reaction	Optically thin rate (s^{-1})	γ	Ref.	$36 \times 10^{-18} \left(\frac{T}{200}\right)^{0.35} \exp\left(-\frac{161.3}{70}\right)$	83
166	U= 1 a U 1 a=	$R_{166} = 7.1 \times 10^{-7}$	0.5	1	1×10^{-19} $T \le 300 \text{ K}$	84
166	$H^- + \gamma \rightarrow H + e^-$		0.5	1		85
167	$H_2^+ + \gamma \rightarrow H + H^+$	$R_{167} = 1.1 \times 10^{-9}$	1.9	2	$46 \times 10^{-16} T^{-0.5} \exp\left(-\frac{4.93}{10}\right)$	86
168	$H_2 + \gamma \rightarrow H + H$	$R_{168} = 5.6 \times 10^{-11}$	See §2.2	3	$0 \times 10^{-16} \left(\frac{T}{300}\right)^{-0.2}$	87
169	$H_3^+ + \gamma \rightarrow H_2 + H^+$	$R_{169} = 4.9 \times 10^{-13}$	1.8	4	5×10^{-10} $T \leq 300 \text{ K}$	84
170	$H_3^+ + \gamma \rightarrow H_2^+ + H$	$R_{170} = 4.9 \times 10^{-13}$	2.3	4	$14 \times 10^{-18} \left(\frac{T}{300}\right)^{-0.15} \exp\left(\frac{68}{T}\right)$ $T > 300 \text{ K}$	
171	$C + \gamma \rightarrow C^+ + e^-$	$R_{171} = 3.1 \times 10^{-10}$	3.0	5	5×10^{-13}	28
172	$C^- + \gamma \rightarrow C + e^-$	$R_{172} = 2.4 \times 10^{-7}$	0.9	6		28
173	$CH + \gamma \rightarrow C + H$	$R_{173} = 8.7 \times 10^{-10}$	1.2	7	$9 \times 10^{-20} \left(\frac{1}{200} \right)$	82
174	$CH + \gamma \rightarrow CH^+ + e^-$	$R_{174} = 7.7 \times 10^{-10}$	2.8	8		88
175	$\rm CH^+ + \gamma \rightarrow \rm C + \rm H^+$		2.5	7	$32 \times 10^{-32} \left(\frac{3}{200}\right)$ $T \leq 300 \text{ K}$	89
176	$CH_2 + \gamma \rightarrow CH + H$	$R_{176} = 7.1 \times 10^{-10}$	1.7	7	$32 \times 10^{-32} \left(\frac{T}{300}\right)^{-1.0}$ $T > 300 \text{ K}$	90
177	$CH_2 + \gamma \rightarrow CH_2^+ + e^-$	$R_{177} = 5.9 \times 10^{-10}$	2.3	6	$8 \times 10^{-31} T^{-0.5}$	91
178	$CH_2^+ + \gamma \rightarrow CH^+ + H$	$R_{178} = 4.6 \times 10^{-10}$	1.7	9	-16	92 93
179	$CH_3^+ + \gamma \rightarrow CH_2^+ + H$	$R_{179} = 1.0 \times 10^{-9}$	1.7	6	$99 \times 10^{-33} \left(\frac{T}{5000}\right)^{-1.6}$ $T \leq 5000 \text{ K}$ $99 \times 10^{-33} \left(\frac{T}{5000}\right)^{-0.64} \exp\left(\frac{5255}{T}\right)$ $T > 5000 \text{ K}$	
180	$CH_3^+ + \gamma \rightarrow CH^+ + H_2$	$R_{180} = 1.0 \times 10^{-9}$	1.7	6		94
181	$C_2 + \gamma \rightarrow C + C$	$R_{181} = 1.5 \times 10^{-10}$	2.1	7	$16 \times 10^{-29} \left(\frac{T}{300}\right)^{-3.08}$ $T \leq 2000 \text{ K}$	35
182	$O^- + \gamma \rightarrow O + e^-$	$R_{182} = 2.4 \times 10^{-7}$	0.5	6	(300) - (1)	67
183	$OH + \gamma \rightarrow O + H$	$R_{183} = 3.7 \times 10^{-10}$	1.7	10		67 67
184	$OH + \gamma \rightarrow OH^+ + e^-$	$R_{184} = 1.6 \times 10^{-12}$	3.1	6	$33 \times 10^{-32} \left(\frac{T}{200}\right)^{-1.0}$	43
185	$OH^+ + \gamma \rightarrow O + H^+$	$R_{185} = 1.0 \times 10^{-12}$	1.8	4	$56 \times 10^{-31} \left(\frac{7}{300}\right)^{-2.0}$	35
186	$H_2O + \gamma \rightarrow OH + H$	$R_{186} = 6.0 \times 10^{-10}$	1.7	11	$2 \times 10^{-34} \left(\frac{7}{300} \right)^{-1.0}$	37
187	$H_2O + \gamma \rightarrow H_2O^+ + e^-$	$R_{187} = 3.2 \times 10^{-11}$	3.9	8	11 C m 3 0.44	95
188	$H_2O^+ + \gamma \rightarrow H_2^+ + O$	$R_{188} = 5.0 \times 10^{-11}$	See §2.2	12	$0 \times 10^{-18} T^{0.5} f_{\rm A} [1.0 + 0.04(T + T_{\rm d})^{0.5}] f_{\rm A} = \left[1.0 + 10^4 \exp\left(-\frac{600}{T_{\rm d}}\right)\right]^{-1}$	90 96
189	$H_2O^+ + \gamma \rightarrow H^+ + OH$	$R_{189} = 5.0 \times 10^{-11}$	See §2.2	12	$0.002T + 8 \times 10^{-6}T^2]^{-1}$	30
190	$H_2O^+ + \gamma \rightarrow O^+ + H_2$	$R_{190} = 5.0 \times 10^{-11}$	See §2.2	12		_
191	$H_2O^+ + \gamma \rightarrow OH^+ + H$	$R_{191} = 1.5 \times 10^{-10}$	See §2.2	12	$6 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.64}$ 79	
192	$H_3O^+ + \gamma \rightarrow H^+ + H_2O$	$R_{192} = 2.5 \times 10^{-11}$	See §2.2	12	$\times 10^{-8} \left(\frac{T}{300}\right)^{-0.64}$ 79	
193	$H_3O^+ + \gamma \rightarrow H_2^+ + OH$	$R_{193} = 2.5 \times 10^{-11}$	See §2.2	12	$\times 10^{-7} \left(\frac{T}{200}\right)^{-1.0}$ 28	
194	$H_3O^+ + \gamma \rightarrow H_2O^+ + H$	$R_{194} = 7.5 \times 10^{-12}$	See §2.2	12	× 10 ⁻⁹ 28	
195	$H_3O^+ + \gamma \rightarrow OH^+ + H_2$		See §2.2	12	$\times 10^{-9}$ 28 $\times 10^{-10}$ 28	
196	$O_2 + \gamma \rightarrow O_2^+ + e^-$	$R_{196} = 5.6 \times 10^{-11}$	3.7	7	$\times 10^{-10}$ 28	
197	$O_2 + \gamma \rightarrow O + O$	$R_{197} = 7.0 \times 10^{-10}$	1.8	7	× 10 ⁻¹³ 28	
198	$CO + \gamma \rightarrow C + O$	$R_{198} = 2.0 \times 10^{-10}$	See §2.2	13	$\times 10^{-10}$ 28 $\times 10^{-10}$ 28	
				** 1.4.0	× 10 ⁻¹⁰ 28	
		$CO^+ + C$ 140 $O^- + C \rightarrow CO + CO^+$		$k_{140} = k_{140}$	5.0×10^{-10} 28	
	87 H	$\mathrm{CO}^+ + \mathrm{H}_2\mathrm{O} \rightarrow \mathrm{CO} + \mathrm{H}_3\mathrm{O}^+ k_{87} =$	2.5×10^{-5}		62	



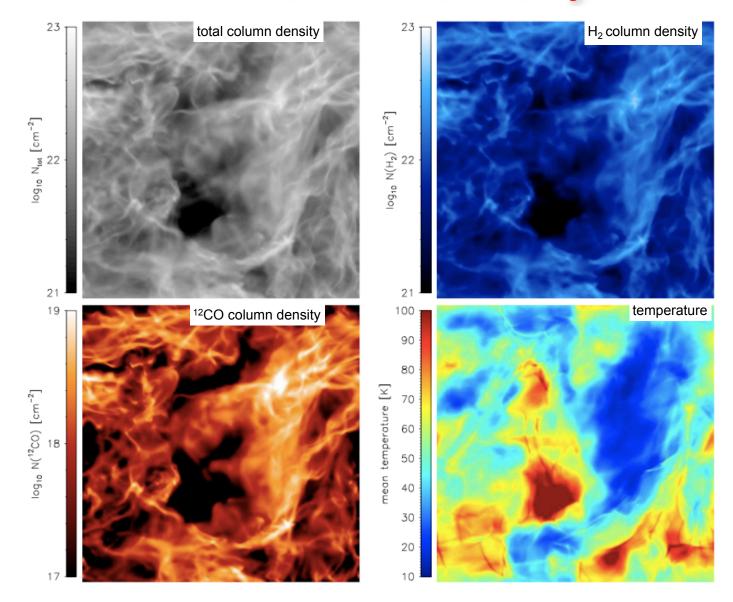
	Table B1. No. Rea 1 H +	15 11-	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$ \begin{array}{l} e^+ \rightarrow He + H + H^+ \\ + \rightarrow CH^+ + H \\ H^+ \rightarrow CH_2^+ + H \\ H^+ \rightarrow CH_2^+ + H \\ H^+ \rightarrow CH_2^+ + H \\ H^+ \rightarrow OH^+ + H \\ H^+ \rightarrow OH^+ + He + H \\ H^+ \rightarrow OH + He + H^+ \\ He^+ \rightarrow OH + He + H^+ \\ He^+ \rightarrow OH^+ + He + H^+ \\ \end{array} $	$k_{90} = 1$ $k_{91} = 1$ $g_{2} =$ $g_{3} =$ $k_{94} = 2$ $k_{95} = 1$ $k_{96} = 6$	$\begin{array}{c} 7 \times 10^{-14} \exp\left(\frac{35}{T}\right) \\ 9 \times 10^{-9} \\ 4 \times 10^{-9} \\ 5 \\ 5 \\ 1 \times 10^{-9} \\ 1 \times 10^{-9} \\ 9 \times 10^{-9} \\ 9 \times 10^{-9} \\ 9 \times 10^{-10} \\ 6 \times 10^{-10} \end{array}$	2	63 28 28 28 28 28 28 28 64 65 65	ARIHTALSW
able	B2. List of		emical reactions included in o	our chemical mod	lel	25×10^{-15} 0×10^{-17} 0×10^{-17}			8
No.	Reaction		Optically thin rate	$(s^{-1}) \gamma$	Ref.	$36 \times 10^{-18} \left(\frac{T}{2000}\right)^{0.3}$	$\frac{5}{\exp(-\frac{161.3}{T})}$		8
166	$H^- + \gamma \rightarrow$	$H + e^{-}$	$R_{166} = 7.1 \times 10^{-7}$	0.5	1	1×10^{-19}		$T \leqslant 300 \ {\rm K}$	8
167	$H_2^+ + \gamma \rightarrow$		$R_{167} = 1.1 \times 10^{-9}$	1.9	2	$09 \times 10^{-17} \left(\frac{T}{300}\right)^{0.3}$	$\exp\left(-\frac{1629}{T}\right)$	T > 300 K	8
168	$H_2^2 + \gamma \rightarrow 1$		$R_{168} = 5.6 \times 10^{-11}$	See §2.2	3	$46 \times 10^{-16} T^{-0.5} \exp (10^{-16} (T)^{-0.2})$	$(-\frac{1}{T^{2/3}})$		8
169	$H_3^+ + \gamma \rightarrow$			1.8	4	$0 \times 10^{-16} \left(\frac{T}{300}\right)^{-0.2}$ 5×10^{-18}		$T \leqslant 300 \text{ K}$	8
170	$H_3^+ + \gamma \rightarrow$			2.3	4	$14 \times 10^{-18} \left(\frac{T}{300}\right)^{-0}$	$\frac{15}{\exp\left(\frac{68}{T}\right)}$	T > 300 K	
171	$C + \gamma \rightarrow C$		P 2 1 v 10-10	2.0	5	T v 10-15	• (1)		1
172	$C^- + \gamma \rightarrow$	Table	B3. List of reactions include	d in our chemical	l model	that involve cosmi	c rays or cos	mic-ray induced U	UV emission
173	$CH + \gamma \rightarrow$						-	-	
174	$CH + \gamma \rightarrow$	No.	Reaction	Rate $(s^{-1}\zeta_{H}^{-1})$		Ref.			
175	$CH^+ + \gamma$			THE (F SH)					
176	$CH_2 + \gamma -$	199	$H + c.r. \rightarrow H^+ + e^-$	D 1.0					
				$R_{199} = 1.0$					
177	$CH_2 + \gamma$	200	$He + c.r. \rightarrow He^+ + e^-$	$R_{200} = 1.1$		1			
177 178	$CH_2 + \gamma - CH_2^+ + \gamma$	200 201	$He + c.r. \rightarrow He^+ + e^-$ $H_2 + c.r. \rightarrow H^+ + H + e^-$	$R_{200} = 1.1$ $R_{201} = 0.037$		1			
177 178 179	$\begin{array}{c} \operatorname{CH}_2+\gamma - \\ \operatorname{CH}_2^++\gamma + \\ \operatorname{CH}_3^++\gamma \end{array}$	200 201 202	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \rightarrow \mathrm{He}^+ + \mathrm{e}^- \\ \mathrm{H}_2 + \mathrm{c.r.} \rightarrow \mathrm{H}^+ + \mathrm{H} + \mathrm{e}^- \\ \mathrm{H}_2 + \mathrm{c.r.} \rightarrow \mathrm{H} + \mathrm{H} \end{array}$	$R_{200} = 1.1$ $R_{201} = 0.037$ $R_{202} = 0.22$	-4	1 1 1 1			
177 178 179 180	$\begin{array}{c} \mathrm{CH}_2 + \gamma \\ \mathrm{CH}_2^+ + \gamma \\ \mathrm{CH}_3^+ + \gamma \\ \mathrm{CH}_3^+ + \gamma \end{array}$	200 201 202 203	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \rightarrow \mathrm{He}^+ + \mathrm{e}^- \\ \mathrm{H}_2 + \mathrm{c.r.} \rightarrow \mathrm{H}^+ + \mathrm{H} + \mathrm{e}^- \\ \mathrm{H}_2 + \mathrm{c.r.} \rightarrow \mathrm{H} + \mathrm{H} \\ \mathrm{H}_2 + \mathrm{c.r.} \rightarrow \mathrm{H}^+ + \mathrm{H}^- \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \end{array}$) ⁻⁴	1 1 1 1			
177 178 179 180 181	$\begin{array}{c} \mathrm{CH}_2+\gamma -\\ \mathrm{CH}_2^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{CH}_3^++\gamma \end{array}$	200 201 202 203 204	$\begin{array}{l} {\rm He} + {\rm c.r.} \to {\rm He}^+ + {\rm e}^- \\ {\rm H}_2 + {\rm c.r.} \to {\rm H}^+ + {\rm H} + {\rm e}^- \\ {\rm H}_2 + {\rm c.r.} \to {\rm H} + {\rm H} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H}^+ + {\rm H}^- \\ {\rm H}_2 + {\rm c.r.} \to {\rm H}_2^+ + {\rm e}^- \end{array}$	$\begin{aligned} R_{200} &= 1.1 \\ R_{201} &= 0.037 \\ R_{202} &= 0.22 \\ R_{203} &= 6.5 \times 10 \\ R_{204} &= 2.0 \end{aligned}$	ŋ−4	1 1 1 1			
177 178 179 180 181 182	$\begin{array}{c} \mathrm{CH}_2+\gamma -\\ \mathrm{CH}_2^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{C}_2+\gamma \rightarrow \\ \mathrm{O}^-+\gamma -\end{array}$	200 201 202 203 204 205	$\begin{array}{l} {\rm He} + {\rm c.r.} \to {\rm He}^+ + {\rm e^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+} + {\rm H} + {\rm e^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H} + {\rm H} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+} + {\rm H^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H_2^+} + {\rm e^-} \\ {\rm C} + {\rm c.r.} \to {\rm C^+} + {\rm e^-} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \end{array}$)-4	1 1 1 1 1			
177 178 179 180 181 182 183	$\begin{array}{c} \mathrm{CH}_2+\gamma -\\ \mathrm{CH}_2^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{C}_2+\gamma \rightarrow \\ \mathrm{O}^-+\gamma \rightarrow \\ \mathrm{OH}+\gamma -\end{array}$	200 201 202 203 204 205 206	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \to \mathrm{He}^+ + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H} + \mathrm{H} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H_2^+} + \mathrm{e^-} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{O} + \mathrm{c.r.} \to \mathrm{O^+} + \mathrm{e^-} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \end{array}$	ŋ−4	1 1 1 1 1 1			
177 178 179 180 181 182 183 184	$\begin{array}{c} \mathrm{CH}_2+\gamma -\\ \mathrm{CH}_2^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{C}_2+\gamma \rightarrow \\ \mathrm{O}^-+\gamma -\\ \mathrm{OH}+\gamma -\\ \mathrm{OH}+\gamma - \end{array}$	200 201 202 203 204 205 206 207	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \to \mathrm{He}^{+} + \mathrm{e^{-}} \\ \mathrm{H}_{2} + \mathrm{c.r.} \to \mathrm{H^{+}} + \mathrm{H} + \mathrm{e^{-}} \\ \mathrm{H}_{2} + \mathrm{c.r.} \to \mathrm{H^{+}} + \mathrm{H} \\ \mathrm{H}_{2} + \mathrm{c.r.} \to \mathrm{H^{+}} + \mathrm{H^{-}} \\ \mathrm{H}_{2} + \mathrm{c.r.} \to \mathrm{H^{+}}_{2} + \mathrm{e^{-}} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^{+}} + \mathrm{e^{-}} \\ \mathrm{O} + \mathrm{c.r.} \to \mathrm{O^{+}} + \mathrm{e^{-}} \\ \mathrm{O} + \mathrm{c.r.} \to \mathrm{O^{+}} + \mathrm{e^{-}} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \end{array}$)-4	1 1 1 1 1 1 1 1 1 2			
177 178 179 180 181 182 183 184 185	$\begin{array}{c} \mathrm{CH}_2+\gamma \\ \mathrm{CH}_2^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{C}_2+\gamma \rightarrow \\ \mathrm{O}^-+\gamma - \\ \mathrm{OH}+\gamma - \\ \mathrm{OH}+\gamma - \\ \mathrm{OH}+\gamma - \\ \mathrm{OH}^++\gamma \end{array}$	200 201 202 203 204 205 206 207 208	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \to \mathrm{He}^+ + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H_2^+} + \mathrm{e^-} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{O} + \mathrm{c.r.} \to \mathrm{O^+} + \mathrm{e^-} \\ \mathrm{CO} + \mathrm{c.r.} \to \mathrm{CO^+} + \mathrm{e^-} \\ \mathrm{C} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{e^-} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \end{array}$)-4	1 1 1 1 1 1 1 2 3			
177 178 179 180 181 182 183 184	$\begin{array}{c} \mathrm{CH}_2+\gamma \\ \mathrm{CH}_2^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{C}_2+\gamma \rightarrow \\ \mathrm{O}^-+\gamma \rightarrow \\ \mathrm{OH}+\gamma \rightarrow \\ \mathrm{OH}+\gamma \rightarrow \\ \mathrm{OH}+\gamma - \\ \mathrm{OH}^++\gamma \\ \mathrm{H}_2\mathrm{O}+\gamma \end{array}$	200 201 202 203 204 205 206 207	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \to \mathrm{He}^+ + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H_2^+} + \mathrm{e^-} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{O} + \mathrm{c.r.} \to \mathrm{O^+} + \mathrm{e^-} \\ \mathrm{CO} + \mathrm{c.r.} \to \mathrm{CO^+} + \mathrm{e^-} \\ \mathrm{CH} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H^-} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \\ R_{209} = 4000 \end{array}$)-4	1 1 1 1 1 1 1 1 2 3 3			
177 178 179 180 181 182 183 184 185 186	$\begin{array}{c} \mathrm{CH}_2+\gamma \\ \mathrm{CH}_2^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{C}_2+\gamma \rightarrow \\ \mathrm{O}^-+\gamma - \\ \mathrm{OH}+\gamma - \\ \mathrm{OH}+\gamma - \\ \mathrm{OH}+\gamma - \\ \mathrm{OH}^++\gamma \end{array}$	200 201 202 203 204 205 206 207 208 209	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \to \mathrm{He}^+ + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+_2} + \mathrm{e^-} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{O} + \mathrm{c.r.} \to \mathrm{O^+} + \mathrm{e^-} \\ \mathrm{CO} + \mathrm{c.r.} \to \mathrm{CO^+} + \mathrm{e^-} \\ \mathrm{CH} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \\ \mathrm{CH^+} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \\ R_{209} = 4000 \\ R_{210} = 960 \end{array}$)-4	3			
177 178 179 180 181 182 183 184 185 186 187	$\begin{array}{c} \mathrm{CH}_2+\gamma \\ \mathrm{CH}_2^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{C}_2+\gamma \rightarrow \\ \mathrm{O}^-+\gamma \rightarrow \\ \mathrm{OH}+\gamma \rightarrow \\ \mathrm{OH}+\gamma \rightarrow \\ \mathrm{OH}+\gamma \rightarrow \\ \mathrm{OH}^++\gamma \\ \mathrm{H}_2\mathrm{O}+\gamma \\ \mathrm{H}_2\mathrm{O}+\gamma \\ \mathrm{H}_2\mathrm{O}+\gamma \end{array}$	200 201 202 203 204 205 206 207 208 209 210	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \to \mathrm{He}^+ + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{e^-} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{C} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{CH} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \\ \mathrm{CH^+} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH^+} + \mathrm{H} \\ \mathrm{CH_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{e^-} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \\ R_{209} = 4000 \end{array}$)-4	3			
177 178 179 180 181 182 183 184 185 186 187 188	$\begin{array}{c} \mathrm{CH}_2+\gamma \\ \mathrm{CH}_2^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{CH}_3^++\gamma \\ \mathrm{C}_2+\gamma \rightarrow \\ \mathrm{O}^-+\gamma \rightarrow \\ \mathrm{OH}+\gamma \rightarrow \\ \mathrm{OH}+\gamma \rightarrow \\ \mathrm{OH}+\gamma \rightarrow \\ \mathrm{OH}^++\gamma \\ \mathrm{H}_2\mathrm{O}+\gamma \\ \mathrm{H}_2\mathrm{O}+\gamma \\ \mathrm{H}_2\mathrm{O}^++\gamma \end{array}$	200 201 202 203 204 205 206 207 208 209 210 211 212	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \to \mathrm{He}^+ + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+_2} + \mathrm{e^-} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{O} + \mathrm{c.r.} \to \mathrm{O^+} + \mathrm{e^-} \\ \mathrm{CO} + \mathrm{c.r.} \to \mathrm{CO^+} + \mathrm{e^-} \\ \mathrm{CH} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \\ \mathrm{CH^+} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \\ R_{209} = 4000 \\ R_{210} = 960 \\ R_{211} = 2700 \end{array}$)-4	3			
177 178 179 180 181 182 183 184 185 186 187 188 189	$\begin{array}{c} {\rm CH}_2 + \gamma - \\ {\rm CH}_2^+ + \gamma \\ {\rm CH}_3^+ + \gamma - \\ {\rm CH}_3^+ + \gamma - \\ {\rm C}_2 + \gamma \rightarrow \\ {\rm O}^- + \gamma - \\ {\rm OH} + \gamma - \\ {\rm H}_2{\rm O} + \gamma - \\ {\rm H}_2{\rm O} + \gamma - \\ {\rm H}_2{\rm O} + \gamma - \\ {\rm H}_2{\rm O}^+ + \gamma \end{array}$	200 201 202 203 204 205 206 207 208 209 210 211 212	$\begin{array}{l} {\rm He} + {\rm c.r.} \to {\rm He}^+ + {\rm e^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+} + {\rm H} + {\rm e^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H} + {\rm H} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+} + {\rm H^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+}_2 + {\rm e^-} \\ {\rm C} + {\rm c.r.} \to {\rm C^+} + {\rm e^-} \\ {\rm O} + {\rm c.r.} \to {\rm O^+} + {\rm e^-} \\ {\rm CO} + {\rm c.r.} \to {\rm CO^+} + {\rm e^-} \\ {\rm CH} + \gamma_{{\rm c.r.}} \to {\rm C} + {\rm H} \\ {\rm CH}^+ + \gamma_{{\rm c.r.}} \to {\rm CH} + {\rm H} \\ {\rm CH}_2 + \gamma_{{\rm c.r.}} \to {\rm CH}_2^+ + {\rm e^-} \\ {\rm CH}_2 + \gamma_{{\rm c.r.}} \to {\rm CH} + {\rm H} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \\ R_{209} = 4000 \\ R_{210} = 960 \\ R_{211} = 2700 \\ R_{212} = 2700 \\ R_{213} = 1300 \\ R_{214} = 2800 \end{array}$)-4	3 3 1 1			
177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192	$\begin{array}{c} {\rm CH}_2 + \gamma - \\ {\rm CH}_2^+ + \gamma \\ {\rm CH}_3^+ + \gamma \\ {\rm CH}_3^+ + \gamma - \\ {\rm C}_2 + \gamma \rightarrow \\ {\rm O}^- + \gamma \rightarrow \\ {\rm OH} + \gamma \rightarrow \\ {\rm OH} + \gamma \rightarrow \\ {\rm OH} + \gamma \rightarrow \\ {\rm OH}^+ + \gamma - \\ {\rm H}_2{\rm O} + \gamma - \\ {\rm H}_2{\rm O} + \gamma - \\ {\rm H}_2{\rm O}^+ + \gamma \\ {\rm H}_3{\rm O}^+ + \gamma \end{array}$	200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215	$\begin{array}{l} {\rm He} + {\rm c.r.} \to {\rm He}^+ + {\rm e^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+} + {\rm H} + {\rm e^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+} + {\rm H} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+} + {\rm H^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+} + {\rm e^-} \\ {\rm C} + {\rm c.r.} \to {\rm C^+} + {\rm e^-} \\ {\rm O} + {\rm c.r.} \to {\rm O^+} + {\rm e^-} \\ {\rm CO} + {\rm c.r.} \to {\rm CO^+} + {\rm e^-} \\ {\rm CH} + {\rm \gamma}_{{\rm c.r.}} \to {\rm C^+} + {\rm H} \\ {\rm CH^+} + {\rm \gamma}_{{\rm c.r.}} \to {\rm CH} + {\rm H} \\ {\rm CH}^+ + {\rm \gamma}_{{\rm c.r.}} \to {\rm CH} + {\rm H} \\ {\rm CH}_2 + {\rm \gamma}_{{\rm c.r.}} \to {\rm CH} + {\rm H} \\ {\rm CH}_2 + {\rm \gamma}_{{\rm c.r.}} \to {\rm CH} + {\rm H} \\ {\rm C}_2 + {\rm \gamma}_{{\rm c.r.}} \to {\rm CH} + {\rm H} \\ {\rm H}_2 {\rm O} + {\rm \gamma}_{{\rm c.r.}} \to {\rm OH} + {\rm H} \\ {\rm H}_2 {\rm O} + {\rm \gamma}_{{\rm c.r.}} \to {\rm OH} + {\rm H} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \\ R_{209} = 4000 \\ R_{210} = 960 \\ R_{211} = 2700 \\ R_{211} = 2700 \\ R_{212} = 2700 \\ R_{213} = 1300 \\ R_{214} = 2800 \\ R_{215} = 5300 \end{array}$)-4	3 3 1 1 3			
1777 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193	$\begin{array}{c} {\rm CH}_2 + \gamma - \\ {\rm CH}_2^+ + \gamma \\ {\rm CH}_3^+ + \gamma - \\ {\rm CH}_3^+ + \gamma - \\ {\rm C}_2 + \gamma \rightarrow \\ {\rm O}^- + \gamma - \\ {\rm OH} + \gamma - \\ {\rm OH} + \gamma - \\ {\rm OH} + \gamma - \\ {\rm OH}^+ + \gamma - \\ {\rm H}_2{\rm O} + \gamma - \\ {\rm H}_2{\rm O} + \gamma - \\ {\rm H}_2{\rm O}^+ + \gamma \\ {\rm H}_3{\rm O}^+ + \gamma \end{array}$	200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \to \mathrm{He}^+ + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{CO} + \mathrm{c.r.} \to \mathrm{CO^+} + \mathrm{e^-} \\ \mathrm{CH} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \\ \mathrm{CH^+} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \\ \mathrm{CH^+} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH^+} + \mathrm{H} \\ \mathrm{CH_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{e^-} \\ \mathrm{CH_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{H} \\ \mathrm{H_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{H} \\ \mathrm{H_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{H} \\ \mathrm{H_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{H_2^+} + \mathrm{H} \\ \mathrm{H_2} + \gamma_{\mathrm{c.r.}^+} \to \mathrm{H_2^+} + \mathrm{H_2^+} \\ \mathrm{H_2} + \gamma_{\mathrm{C.r.}^+} \to \mathrm{H_2^+} + \mathrm{H_2^+} \\ \mathrm{H_2} + \mathrm{H_2^+} + \mathrm{H_2^+}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \\ R_{209} = 4000 \\ R_{210} = 960 \\ R_{211} = 2700 \\ R_{211} = 2700 \\ R_{212} = 2700 \\ R_{213} = 1300 \\ R_{214} = 2800 \\ R_{215} = 5300 \\ R_{216} = 4100 \end{array}$)-4	3 3 1 3 3 3			
177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194	$\begin{array}{c} {\rm CH}_2 + \gamma - \\ {\rm CH}_2^+ + \gamma \\ {\rm CH}_3^+ + \gamma \\ {\rm CH}_3^+ + \gamma - \\ {\rm C}_2 + \gamma \rightarrow \\ {\rm O}^- + \gamma - \\ {\rm OH} + \gamma - \\ {\rm OH} + \gamma - \\ {\rm OH}^+ + \gamma - \\ {\rm H}_2{\rm O} + \gamma - \\ {\rm H}_2{\rm O} + \gamma - \\ {\rm H}_2{\rm O}^+ + \gamma \\ {\rm H}_3{\rm O}^+ + \gamma \\ {\rm H}_3{\rm O}^+ + \gamma \end{array}$	200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \to \mathrm{He}^+ + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{CO} + \mathrm{c.r.} \to \mathrm{CO^+} + \mathrm{e^-} \\ \mathrm{CO} + \mathrm{c.r.} \to \mathrm{CO^+} + \mathrm{e^-} \\ \mathrm{CH} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \\ \mathrm{CH^+} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \\ \mathrm{CH^2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH^+} + \mathrm{H} \\ \mathrm{CH_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{e^-} \\ \mathrm{CH_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{H} \\ \mathrm{CH_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{OH_2^+} + \mathrm{H} \\ \mathrm{O_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{OH_2^+} + \mathrm{H} \\ \mathrm{O_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{OH_2^+} + \mathrm{e^-} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \\ R_{209} = 4000 \\ R_{210} = 960 \\ R_{211} = 2700 \\ R_{212} = 2700 \\ R_{213} = 1300 \\ R_{213} = 1300 \\ R_{214} = 2800 \\ R_{215} = 5300 \\ R_{216} = 4100 \\ R_{217} = 640 \end{array}$		3 1 1 3 3 3 3 3 3			
177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195	$\begin{array}{c} {\rm CH}_2 + \gamma + \\ {\rm CH}_2^+ + \gamma + \\ {\rm CH}_3^+ + \gamma + \\ {\rm C}_2 + \gamma - \\ {\rm OH} + \gamma - \\ {\rm H}_2 {\rm O} + \gamma + \\ {\rm H}_2 {\rm O} + \gamma + \\ {\rm H}_2 {\rm O}^+ + \gamma + \\ {\rm H}_2 {\rm O}^+ + \gamma + \\ {\rm H}_2 {\rm O}^+ + \gamma + \\ {\rm H}_3 {\rm O}^+ + \gamma + \\ \end{array}$	200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \to \mathrm{He}^+ + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{CO} + \mathrm{c.r.} \to \mathrm{CO^+} + \mathrm{e^-} \\ \mathrm{CH} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \\ \mathrm{CH^+} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \\ \mathrm{CH^+} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH^+} + \mathrm{H} \\ \mathrm{CH_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{e^-} \\ \mathrm{CH_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{H} \\ \mathrm{H_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{H} \\ \mathrm{H_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{H} \\ \mathrm{H_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{H_2^+} + \mathrm{H} \\ \mathrm{H_2} + \gamma_{\mathrm{c.r.}^+} \to \mathrm{H_2^+} + \mathrm{H_2^+} \\ \mathrm{H_2} + \gamma_{\mathrm{C.r.}^+} \to \mathrm{H_2^+} + \mathrm{H_2^+} \\ \mathrm{H_2} + \mathrm{H_2^+} + \mathrm{H_2^+}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \\ R_{209} = 4000 \\ R_{210} = 960 \\ R_{211} = 2700 \\ R_{212} = 2700 \\ R_{213} = 1300 \\ R_{213} = 1300 \\ R_{214} = 2800 \\ R_{215} = 5300 \\ R_{216} = 4100 \\ R_{217} = 640 \end{array}$		3 1 1 3 3 3 3 3 3			
177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196	$\begin{array}{c} {\rm CH}_2 + \gamma + \\ {\rm CH}_2^+ + \gamma + \\ {\rm CH}_3^+ + \gamma + \\ {\rm C}_2 + \gamma - \\ {\rm OH} + \gamma - \\ {\rm H}_2 {\rm O} + \gamma + \\ {\rm H}_2 {\rm O} + \gamma + \\ {\rm H}_2 {\rm O}^+ + \gamma + \\ {\rm H}_2 {\rm O}^+ + \gamma + \\ {\rm H}_2 {\rm O}^+ + \gamma + \\ {\rm H}_3 {\rm O}^+ + \gamma + \\ {\rm H}_3 {\rm O}^+ + \gamma + \\ {\rm H}_3 {\rm O}^+ + \gamma - \\ {\rm H}_3 {\rm O}^+ + \gamma + \\ {\rm H}_3 {\rm O}^+ + \gamma - \\ {\rm O}_2 + \gamma \rightarrow \end{array}$	200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218	$\begin{array}{l} {\rm He} + {\rm c.r.} \to {\rm He}^+ + {\rm e^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+} + {\rm H} + {\rm e^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+} + {\rm H^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+} + {\rm H^-} \\ {\rm H}_2 + {\rm c.r.} \to {\rm H^+}_2 + {\rm e^-} \\ {\rm C} + {\rm c.r.} \to {\rm C^+} + {\rm e^-} \\ {\rm O} + {\rm c.r.} \to {\rm O^+} + {\rm e^-} \\ {\rm CO} + {\rm c.r.} \to {\rm CO^+} + {\rm e^-} \\ {\rm CH} + {\rm \gamma}_{{\rm c.r.}} \to {\rm C^+} + {\rm H} \\ {\rm CH^+} + {\rm \gamma}_{{\rm c.r.}} \to {\rm C^+} + {\rm H} \\ {\rm CH}_2 + {\rm \gamma}_{{\rm c.r.}} \to {\rm CH}_2^+ + {\rm e^-} \\ {\rm CH}_2 + {\rm \gamma}_{{\rm c.r.}} \to {\rm CH}_2^+ + {\rm e^-} \\ {\rm CH}_2 + {\rm \gamma}_{{\rm c.r.}} \to {\rm CH}_2^+ + {\rm H} \\ {\rm CH}_2 + {\rm \gamma}_{{\rm c.r.}} \to {\rm CH}_2^+ + {\rm e^-} \\ {\rm CH}_2 + {\rm \gamma}_{{\rm c.r.}} \to {\rm CH}_2^+ + {\rm e^-} \\ {\rm CH}_2 + {\rm \gamma}_{{\rm c.r.}} \to {\rm OH}_2^+ {\rm H} \\ {\rm H}_2 {\rm O} + {\rm \gamma}_{{\rm c.r.}} \to {\rm OH}_2^+ {\rm H} \\ {\rm O}_2 + {\rm \gamma}_{{\rm c.r.}} \to {\rm OH}_2^+ {\rm e^-} \\ {\rm OO}_2 + {\rm \gamma}_{{\rm c.r.}} \to {\rm O}_2^+ {\rm e^-} \\ {\rm CO} + {\rm \gamma}_{{\rm c.r.}} \to {\rm C}_2^- {\rm OH}_2^- \\ \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \\ R_{209} = 4000 \\ R_{210} = 960 \\ R_{211} = 2700 \\ R_{212} = 2700 \\ R_{213} = 1300 \\ R_{213} = 1300 \\ R_{214} = 2800 \\ R_{215} = 5300 \\ R_{216} = 4100 \\ R_{217} = 640 \\ R_{218} = 0.21T^{1/2} \end{array}$		3 3 1 3 3 3 3 3 3 3 1/2 4		25	
177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197	$\begin{array}{c} {\rm CH}_2 + \gamma + \\ {\rm CH}_2^+ + \gamma + \\ {\rm CH}_3^+ + \gamma + \\ {\rm C}_2 + \gamma - \\ {\rm OH} + \gamma - \\ {\rm H}_2 {\rm O} + \gamma + \\ {\rm H}_2 {\rm O} + \gamma + \\ {\rm H}_2 {\rm O}^+ + \gamma + \\ {\rm H}_2 {\rm O}^+ + \gamma + \\ {\rm H}_2 {\rm O}^+ + \gamma + \\ {\rm H}_3 {\rm O}^+ + \gamma + \\ \end{array}$	200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 O + O	$\begin{array}{l} \mathrm{He} + \mathrm{c.r.} \to \mathrm{He}^+ + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} + \mathrm{e^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{H^+} + \mathrm{H^-} \\ \mathrm{H_2} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{C} + \mathrm{c.r.} \to \mathrm{C^+} + \mathrm{e^-} \\ \mathrm{CO} + \mathrm{c.r.} \to \mathrm{CO^+} + \mathrm{e^-} \\ \mathrm{CO} + \mathrm{c.r.} \to \mathrm{CO^+} + \mathrm{e^-} \\ \mathrm{CH} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \\ \mathrm{CH^+} + \gamma_{\mathrm{c.r.}} \to \mathrm{C^+} + \mathrm{H} \\ \mathrm{CH^2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH^+} + \mathrm{H} \\ \mathrm{CH_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{e^-} \\ \mathrm{CH_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{CH_2^+} + \mathrm{H} \\ \mathrm{CH_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{OH_2^+} + \mathrm{H} \\ \mathrm{O_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{OH_2^+} + \mathrm{H} \\ \mathrm{O_2} + \gamma_{\mathrm{c.r.}} \to \mathrm{OH_2^+} + \mathrm{e^-} \end{array}$	$\begin{array}{l} R_{200} = 1.1 \\ R_{201} = 0.037 \\ R_{202} = 0.22 \\ R_{203} = 6.5 \times 10 \\ R_{204} = 2.0 \\ R_{205} = 3.8 \\ R_{206} = 5.7 \\ R_{207} = 6.5 \\ R_{208} = 2800 \\ R_{209} = 4000 \\ R_{210} = 960 \\ R_{211} = 2700 \\ R_{212} = 2700 \\ R_{213} = 1300 \\ R_{213} = 1300 \\ R_{214} = 2800 \\ R_{215} = 5300 \\ R_{216} = 4100 \\ R_{217} = 640 \\ R_{218} = 0.21T^{1/2} \\ \end{array}$		3 1 1 3 3 3 3 3 3		28 28	

(Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)





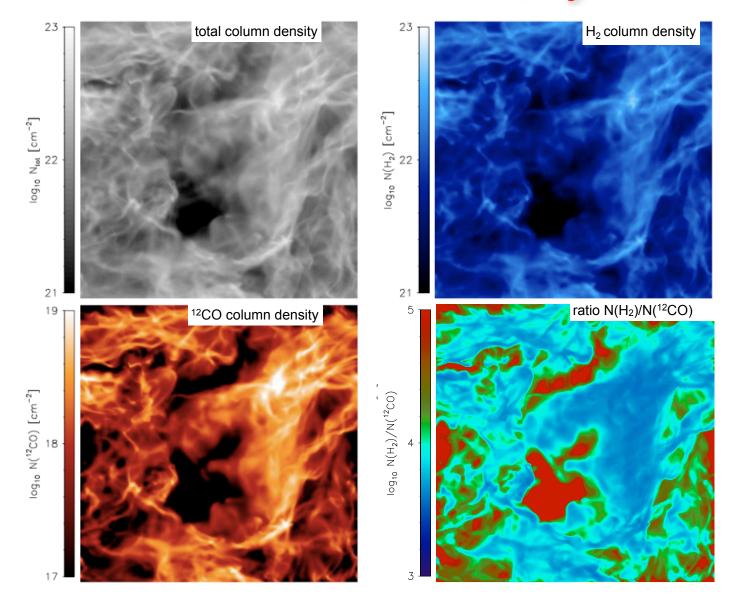
effects of chemistry 1







effects of chemistry 2







example: model of Orion cloud

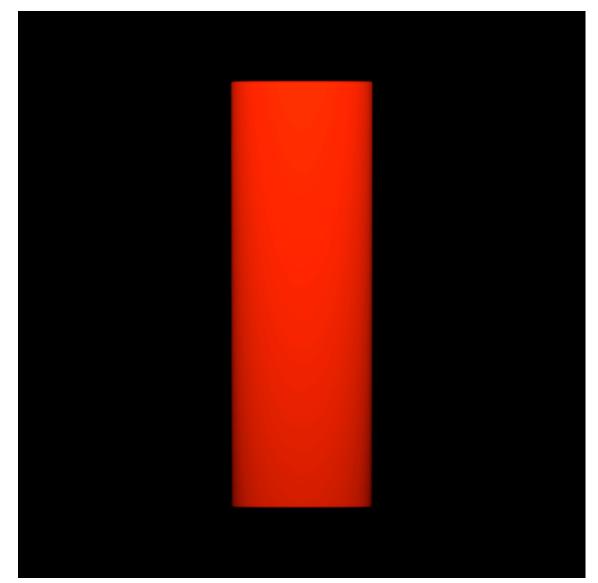
"model" of Orion cloud: 15.000.000 SPH particles, $10^4 M_{sun}$ in 10 pc, mass resolution 0,02 M_{sun} , forms ~2.500 "stars" (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed "star" formation

efficiency varies from 1% to 20%

develops full IMF (distribution of sink particle masses)







example: model of Orion cloud

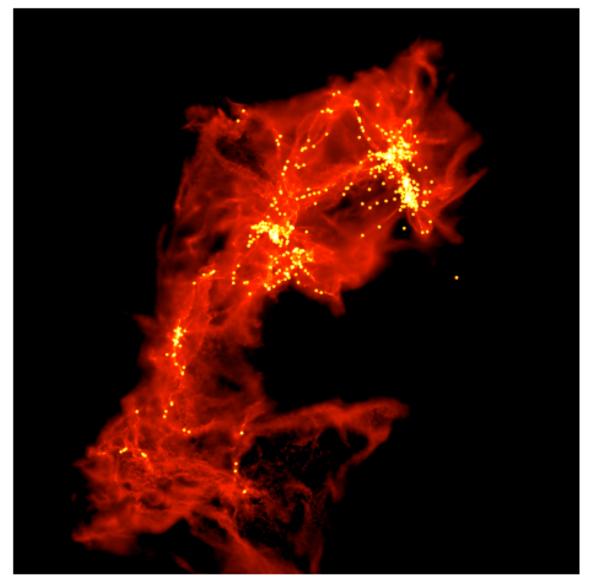
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MASSIVE STARS

- form early in high-density gas clumps (cluster center)
- high accretion rates, maintained for a long time

LOW-MASS STARS

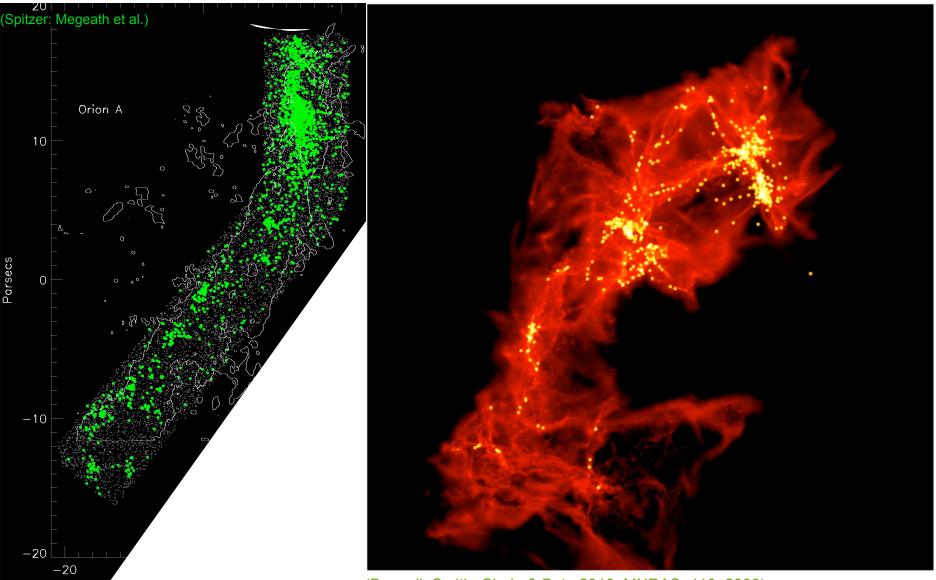
- form later as gas falls into potential well
- high relative velocities
- little subsequent accretion







example: model of Orion cloud



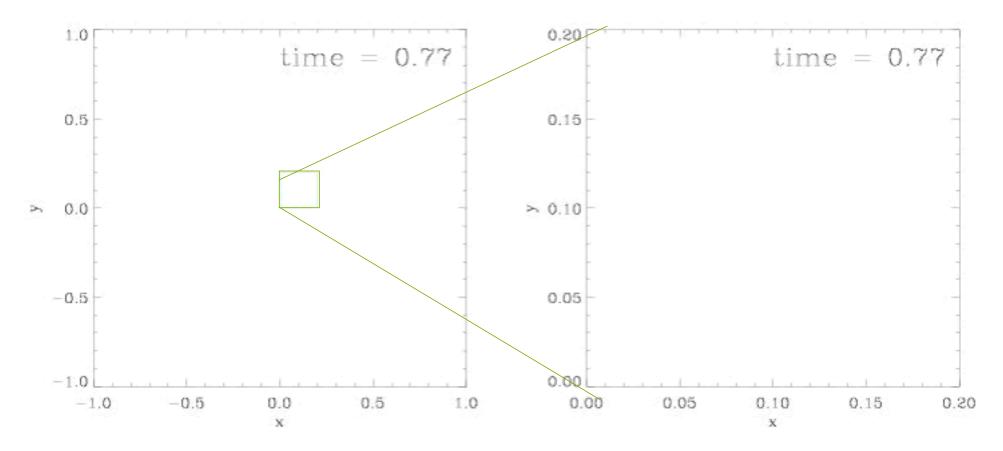
(Bonnell, Smith, Clark, & Bate 2010, MNRAS, 410, 2339)



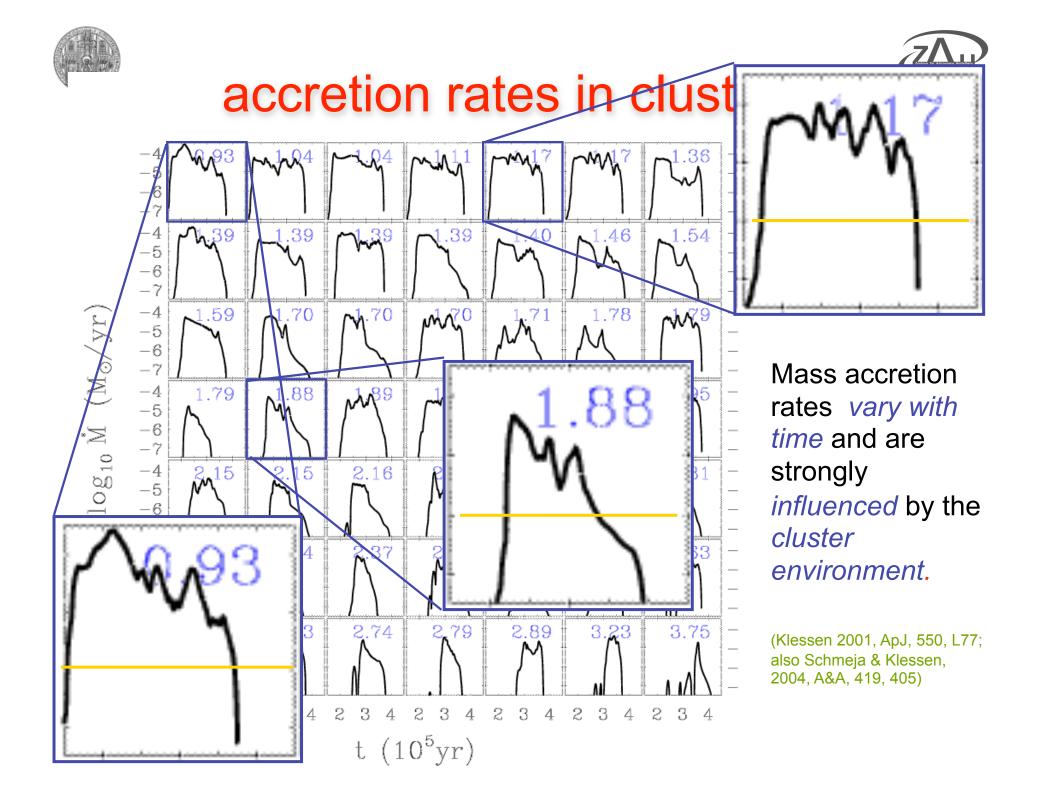


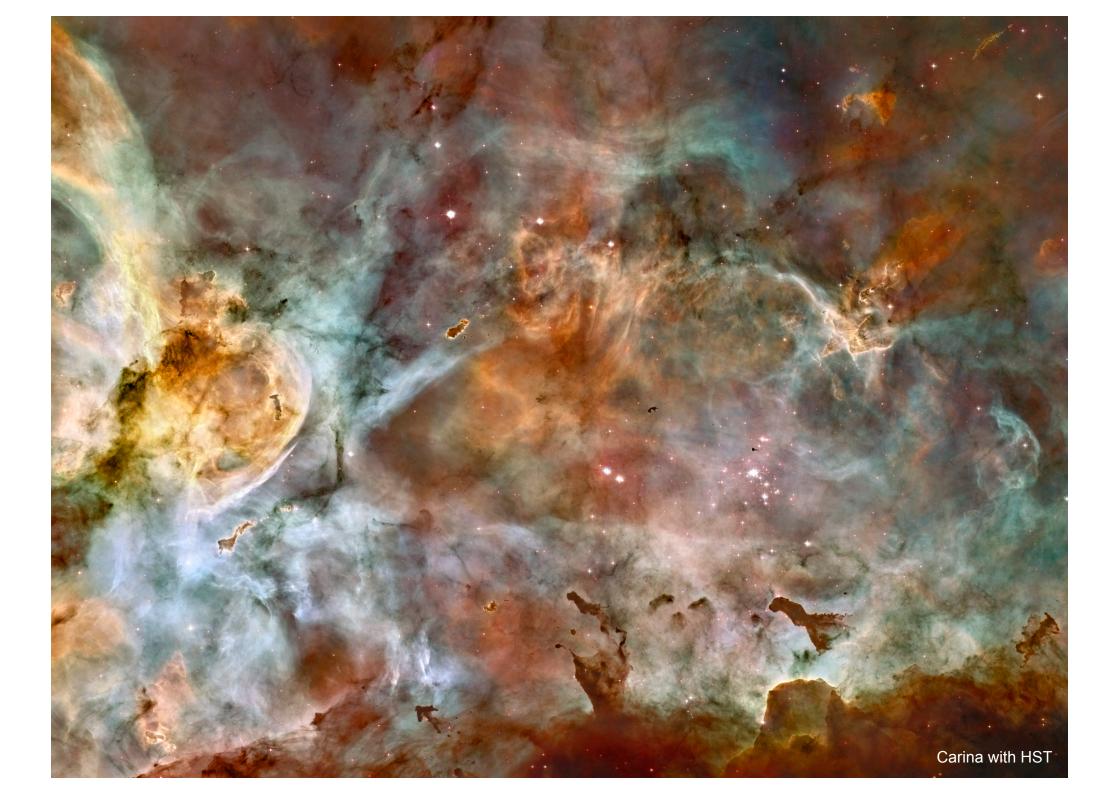
dynamics of nascent star cluster

in dense clusters protostellar interaction may be come important!



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation (from Klessen & Burkert 2000, ApJS, 128, 287)







 stars form from the complex interplay of self-gravity and a large number of competing processes (such as turbulence, B-field, feedback, thermal pressure)

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thanks