Is oxygen well-mixed in the sites where it is found?

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May 2012 · Mapping Oxygen in the Universe, Tenerife

Legal disclaimer

The opinions expressed in this talk are mine alone and should not be taken as representing the views of . . .

. . . my collaborators . . .

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- Fabio de Colle (UC Santa Cruz, USA)
- Garrelt Mellema (Stockholm Observatory, Sweden)

. . . or my employer

- CRyA, UNAM

The flippant answer

Is O well-mixed in the sites where it is found?

Yes. . .

The flippant answer

Is O well-mixed in the sites where it is found?

Yes. . . (mainly). . .

The flippant answer

Is O well-mixed in the sites where it is found?

Yes. . . (mainly). . . but possibly not entirely . . .

Talk based in part on . . .

Henney & Stasińska (2010)

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CAN SOLID BODY DESTRUCTION EXPLAIN ABUNDANCE DISCREPANCIES IN PLANETARY NEBULAE?

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Stasińska et al. (2007)

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Enrichment of the interstellar medium by metal-rich droplets and the abundance bias in H II regions

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. . . and also on . . .

Henney et al. (2009)

Mon. Not. R. Astron. Soc. **398,** 157–175 (2009) doi:10.1111/j.1365-2966.2009.15153.x

Radiation-magnetohydrodynamic simulations of the photoionization of magnetized globules★

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Arthur et al. (2011)

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 14 February 2011 (MN LaTeX style file v2.2)

Radiation-magnetohydrodynamic simulations of H II regions and their associated PDRs in turbulent molecular clouds

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Plan of the talk

Abundance fluctuations in H II regions and PNe

- Observational evidence
- Origin and preservation

Mixing processes

Survival of metal-rich droplets in H II regions

Solid body evaporation in planetary nebulae

Conclusions

Evidence for metallicity fluctuations

- PNe
  - Abundance discrepancies – ADF
    - Liu (2002)
    - Talk by Xuan Fang on Tuesday
  - Indications that $T(\mathrm{ORL}) < T(\mathrm{Bac}) < T(\mathrm{He}) < T(\mathrm{CEL})$
    - The κ-distribution cannot easily explain this
    - (unless we have κ^2 fluctuations!!!)
  - Natural explanation is cool, high-metallicity clumps
- H II regions
  - Yet another explanation for the t^2/ADF phenomenon
  - Advantage is that it requires no additional energy

Where does the metal-rich gas come from?

Different sources required in different classes of object

Planetary nebulae

- Nucleosynthesis products? Probably not
  - Some PNe have evidence for O enrichment
    - O-rich knots in born-again objects (Abel 70, Abel 58)
    - O enhancement in atmospheres of PG1159 stars
  - But unlikely to apply to most PNe (see Amanda Karakas talk on Monday)
- Evaporation of solid bodies? Maybe
  - Survival of planetary systems and/or debris disks through post-MS evolutionary stages
  - Evidence for dust disks around hot WD (Chu et al. 2011)

Where does the metal-rich gas come from?

Different sources required in different classes of object

H II regions

- Evaporation of solid bodies? ~~Probably not~~ Possibly
  - Free-floating planets and planetesimals (KBOs to Jupiters)
  - e.g., Strigari et al. (2011)
- Metal-rich droplets from galactic fountain? Maybe
  - e.g., Tenorio-Tagle (1996), Spitoni et al. (2009)

How can metal-rich fluctuations survive?

- Mixing is the enemy
  - molecular diffusion
  - turbulence
- Turbulence stirs up the gas
  - reducing the spatial scale of the inhomogeneities
  - then molecular diffusion can act to achieve true microscopic mixing

Plan of the talk

Abundance fluctuations in H II regions and PNe

Mixing processes

- Basic definitions
- Molecular and turbulent diffusion

Survival of metal-rich droplets in H II regions

Solid body evaporation in planetary nebulae

Conclusions

Advection, diffusion, sources and sinks

Conservation equation for any quantity *A*

$$\frac{\partial A}{\partial t} + \vec{\nabla} \cdot \vec{F}_A = S_A$$

- S_A: net sources − sinks of A
- $\vec{F}_A$: Flux of A (advective plus diffusive)
  - Advective flux due to bulk velocity u
  - Diffusive flux with diffusion coefficient D

$$\Rightarrow \vec{F}_A = \vec{u}A - D\vec{\nabla}A$$

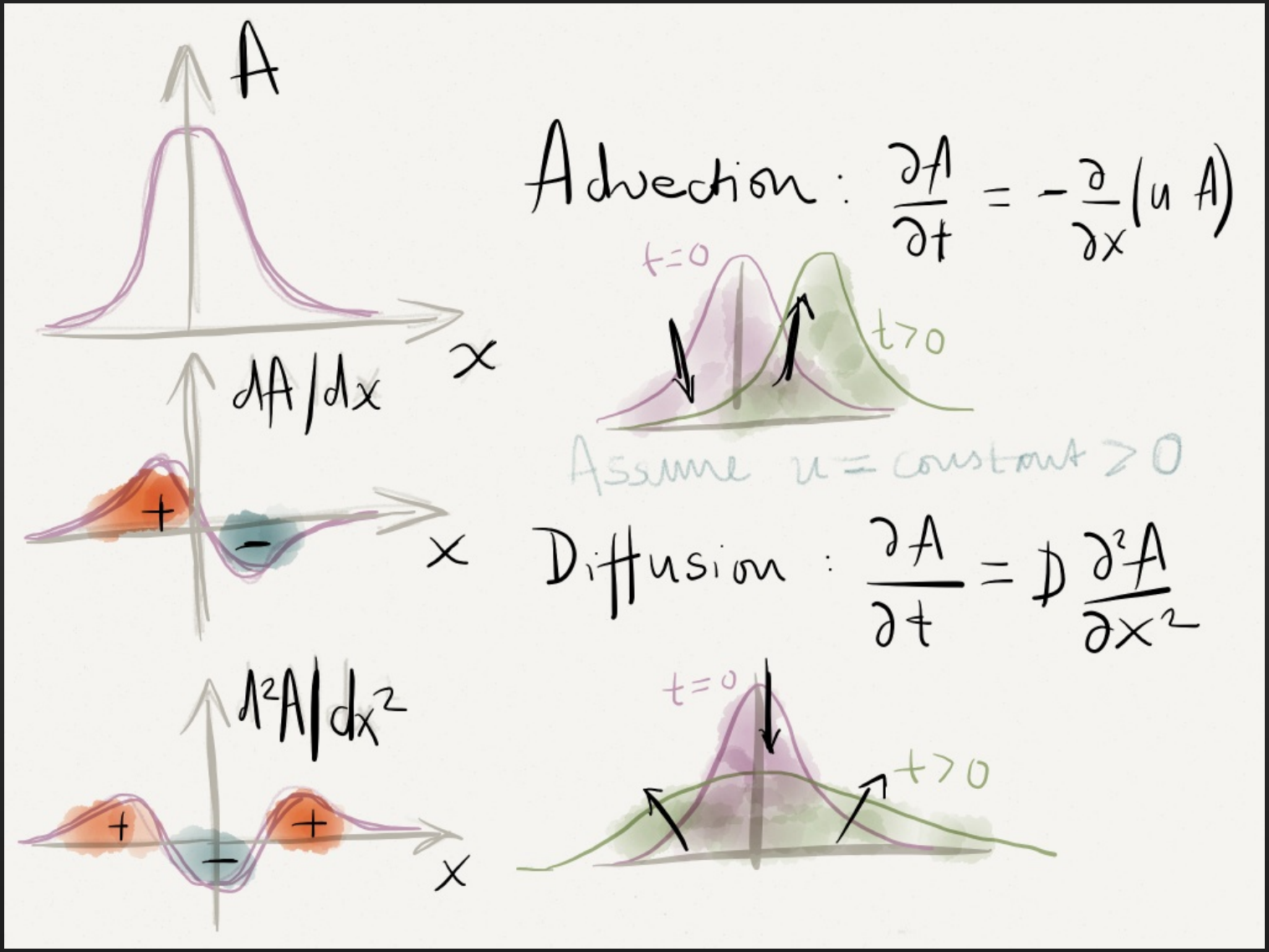
Advection, diffusion, sources and sinks

For constant diffusion coefficient:

$$\frac{\partial A}{\partial t} = S_A - \vec{\nabla} \cdot (A\vec{u}) + D\nabla^2 A$$

$$\text{rate of change} = \text{sources} + \text{diffusion} + \text{advection}$$

Advection/diffusion of a metallicity peak



Molecular diffusion

Random thermal motion of molecules/atoms/ions

Diffusion coefficient ..... $D = u_{\rm rms}\lambda_{\rm mfp}$

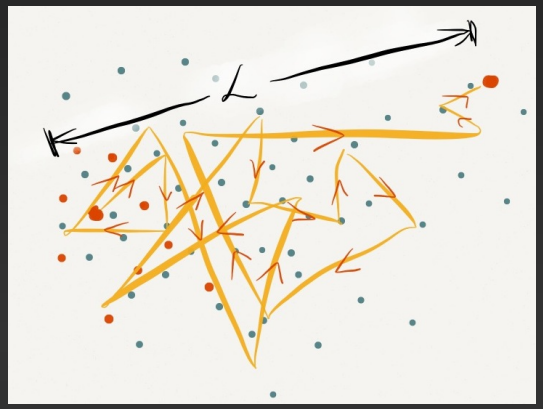
RMS velocity ..... $u_{\rm rms} = (2kT/m)^{1/2}$

Mean free path ..... $\lambda_{\rm mfp} = 1/(n\sigma)$

Molecular diffusion timescale

Random walk to reach a distance *L*

$$t_{\rm d} = L^2/D$$



Example

O^{++} ions moving in a field of H^+ ions

$$\frac{t_{\rm d}}{1\,{\rm Myr}} \simeq 0.3 \left(\frac{L}{1\times10^{15}\,{\rm cm}}\right)^2 \left(\frac{n}{1\,{\rm cm}^{-3}}\right) \left(\frac{T}{10^4\,{\rm yr}}\right)^{-5/2}$$

Molecular diffusion timescale

Object	L (pc)	n (cm^{-3})	T (K)	t_d (yr)	t_{evo} (yr)	L_d (pc)
Giant H II Region	100	10	10 000	3.0×10^{17}	1×10^{7}	5.8×10^{-4}
Planetary nebula	0.1	1×10^{4}	10 000	3.0×10^{14}	1×10^{4}	5.8×10^{-7}
Superbubble	100	0.003	1 000 000	9.1×10^{8}	1×10^{8}	3.3×10^{1}
Molecular cloud	1	1×10^{4}	100	3.0×10^{12}	1×10^{7}	1.8×10^{-3}
Proplyd	3×10^{-4}	1×10^{6}	10 000	2.7×10^{11}	1×10^{2}	5.8×10^{-9}

Diffusion times are *looooong*

See also Tenorio-Tagle (1996), Oey (2003)

Turbulent diffusion: dispersal vs mixing

- Assume turbulent eddies of velocity $u_{\rm turb}$ and size $\ell_{\rm turb}$
- For times greater than the turnover time $t > \ell_{\rm turb}/u_{\rm turb}$, the turbulent diffusion coefficient saturates at

$$D_{\rm turb} = \ell_{\rm turb}\, u_{\rm turb}$$

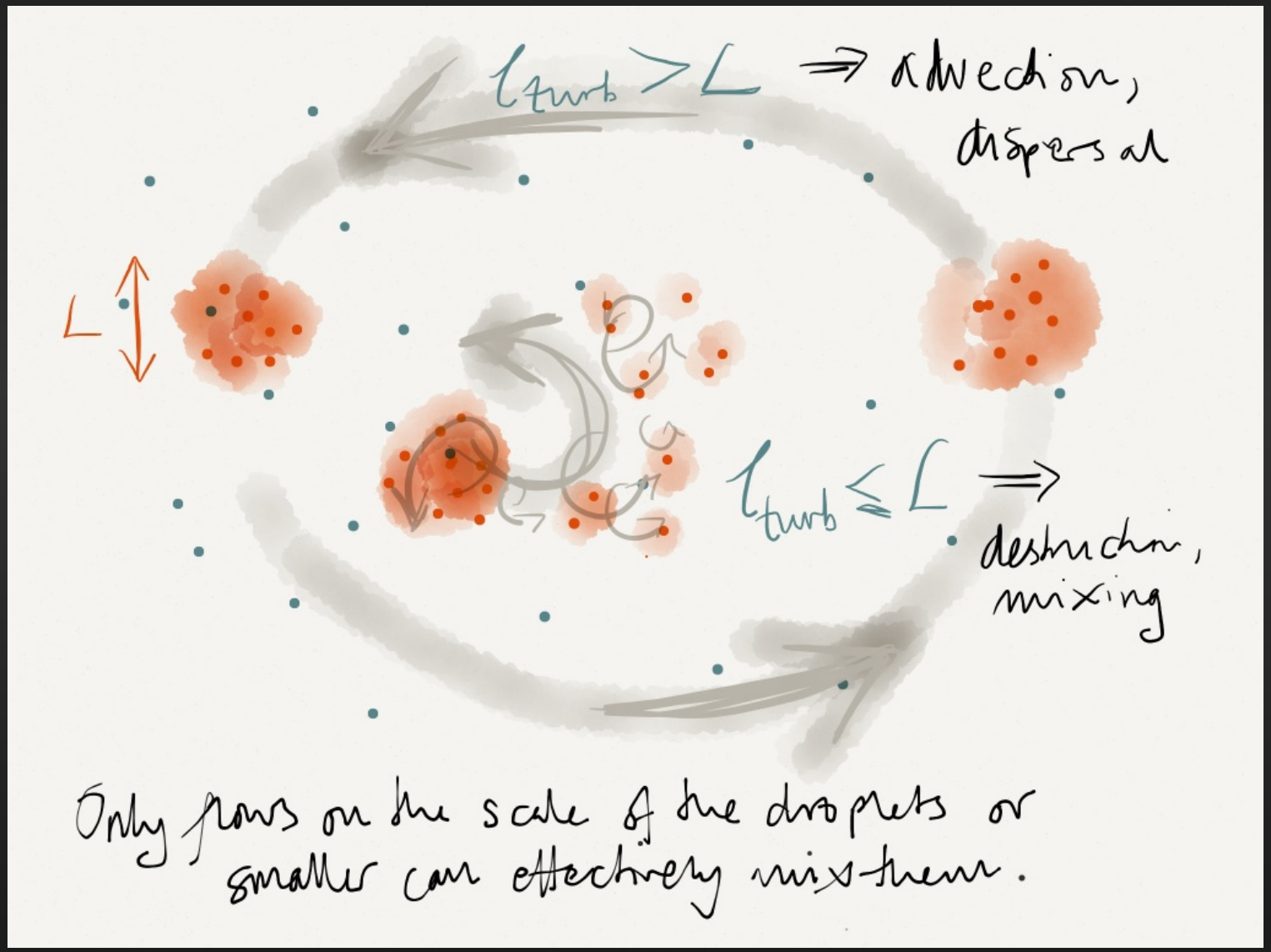
- But $u_{\rm turb}$ varies with scale:

  Kolmogorov: $u_{\rm turb} \sim \ell_{\rm turb}^{1/3}$ (Incompressible)

  Shocks: $u_{\rm turb} \sim \ell_{\rm turb}^{1/2}$ (Highly compressible)

- So, which scale should we pick?

Turbulent diffusion: dispersal vs mixing



Turbulent diffusion: dispersal vs mixing

- Mixing timescale arises from exponental stretching of fluid elements by turbulent shear Pan & Scalo (2007):

$$t_{\rm mix} \sim t_{\rm d,turb} \ln \mathcal{P}$$

  - $\mathcal{P}$ is the Péclet number of the turbulence:

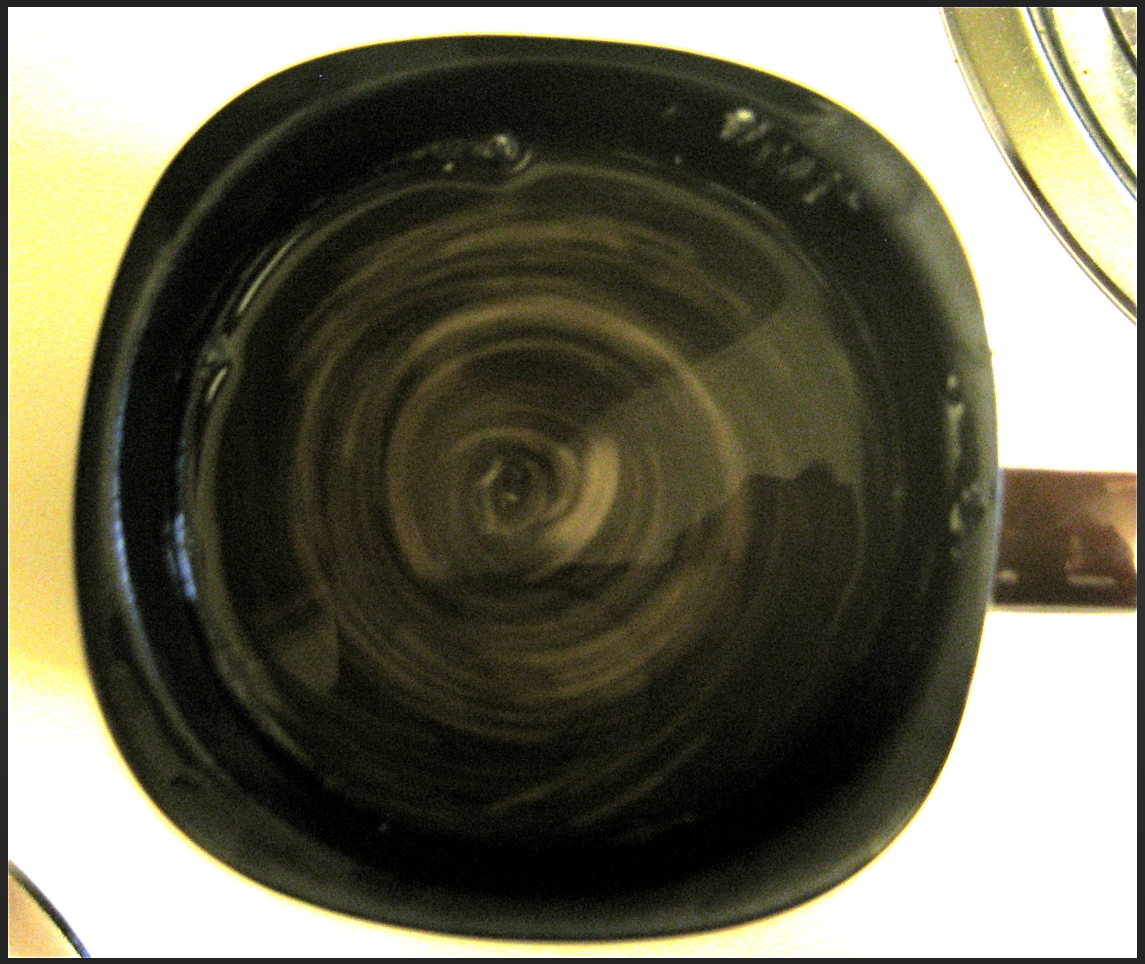
$$\mathcal{P} = D_{\rm turb}/D = \ell_{\rm turb} u_{\rm turb}/D \gg 1$$

  - Similar to the Reynolds number:

$$\mathrm{Re} = \ell_{\rm turb} u_{\rm turb}/\nu \gg 1$$

  where ν is the kinematic viscosity (diffusion coefficient for momentum).

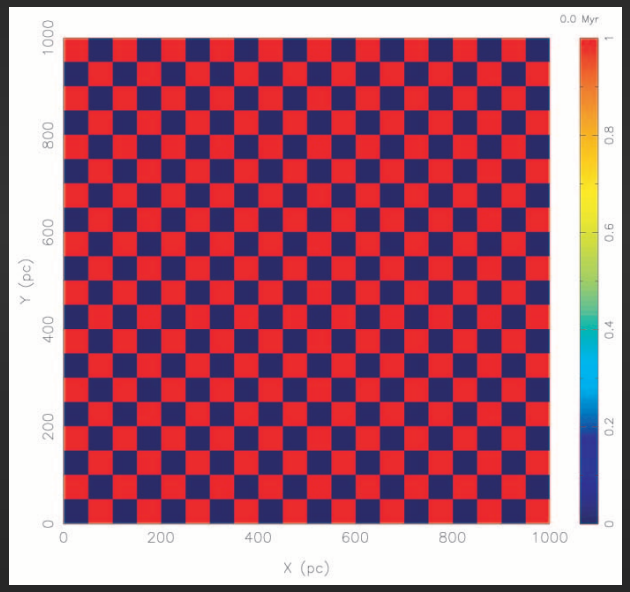
Turbulent diffusion: laboratory analogs



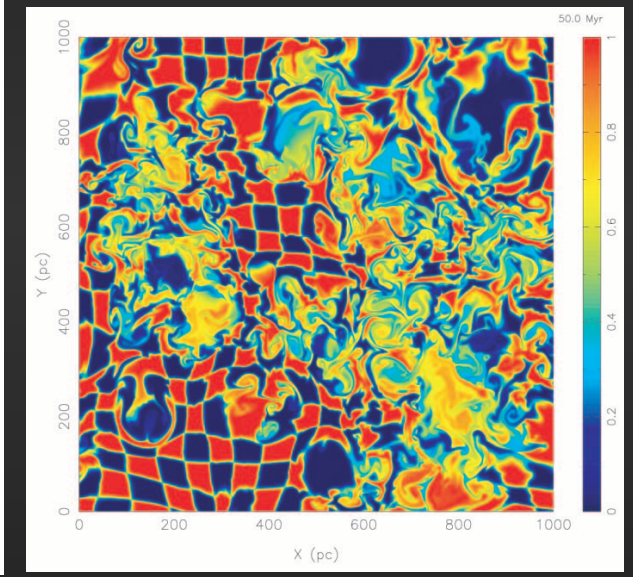
Courtesy of http://puttingweirdthingsincoffee.com

Turbulent diffusion: numerical simulation

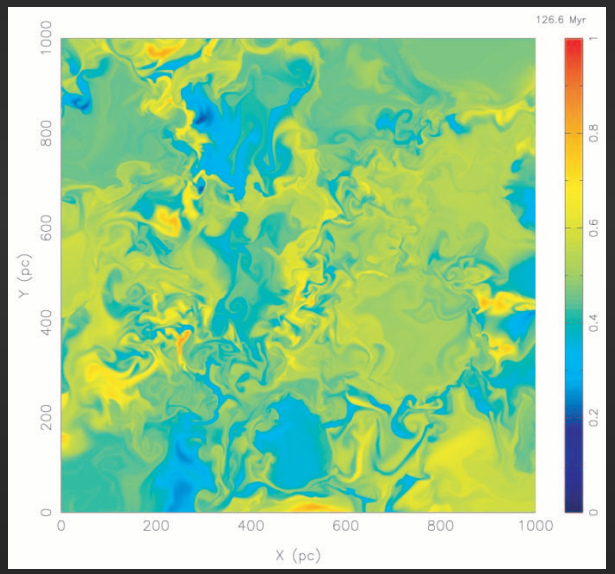
SN-driven ISM (de Avillez & Mac Low 2002)



$t = 0\,\mathrm{Myr}$



$t = 50\,\mathrm{Myr}$



$t = 126.6\,\mathrm{Myr}$

Plan of the talk

Abundance fluctuations in H II regions and PNe

Mixing processes

Survival of metal-rich droplets in H II regions

- Survival times
- Turbulence in H II regions

Solid body evaporation in planetary nebulae

Conclusions

Survival time with no turbulence

Molecular diffusion

Assuming $n \simeq 10^4\,\mathrm{cm}^{-3}$ and $T \simeq 6000\,\mathrm{K}$ for the O-rich droplets, we obtain

$$t_\mathrm{d} \simeq 10^9\,\mathrm{yr}\left(\frac{L}{10^{15}\,\mathrm{cm}}\right)^2,$$

so droplets as small as $10^{14}\,\mathrm{cm}$ could survive for the entire lifetime of a typical H II region.

Survival time *with* turbulence

Turbulent mixing

Assuming turbulent driving by transonic photoevaporation flows at scales of 0.1 to 1 pc, we find

$$t_{\rm mix} \simeq 10^4\,{\rm yr}\left(\frac{L}{10^{15}\,{\rm cm}}\right)^{1/2}\left(\frac{\ell_{\rm out}}{10^{18}\,{\rm cm}}\right)^{1/2}\left(\frac{u_{\rm out}}{10\,{\rm km\ s^{-1}}}\right)^{-1},$$

so turbulent mixing is efficient on timescales much smaller than the H II region lifetime.

Uniform magnetic medium 0–2 Myr

Cold neutral • Warm neutral • Partially ionized • Fully ionized

Krumholz et al. (2007) Arthur et al. (2011)

Globule: 2D simulation

Henney et al. (2009)

Upper panel

Vertical field ⇅

Diagonal field ⇗

Horizontal field ⇆

Diagonal field ⇖

Out-of-plane field ⊗ ⊙

Weak field

Lower panel

Cold neutral

Warm neutral

Partially ionized

Fully ionized

Globule: 3D simulation

Henney et al. (2009)

[N II] Hα [O III]

O star in a turbulent medium: the movie

Sequence

1. Evolution
   0–50 kyr
2. Tumble cube
   @ 50 kyr
3. Evolution
   50–400 kyr
4. Tumble cube
   @ 400 kyr

Color coding

[N II] Hα [O III]

O star in a turbulent, magnetic medium

Arthur et al. (2011)

Upper panels

[N II] Hα [O III]

Lower panels

FIR Cold dust

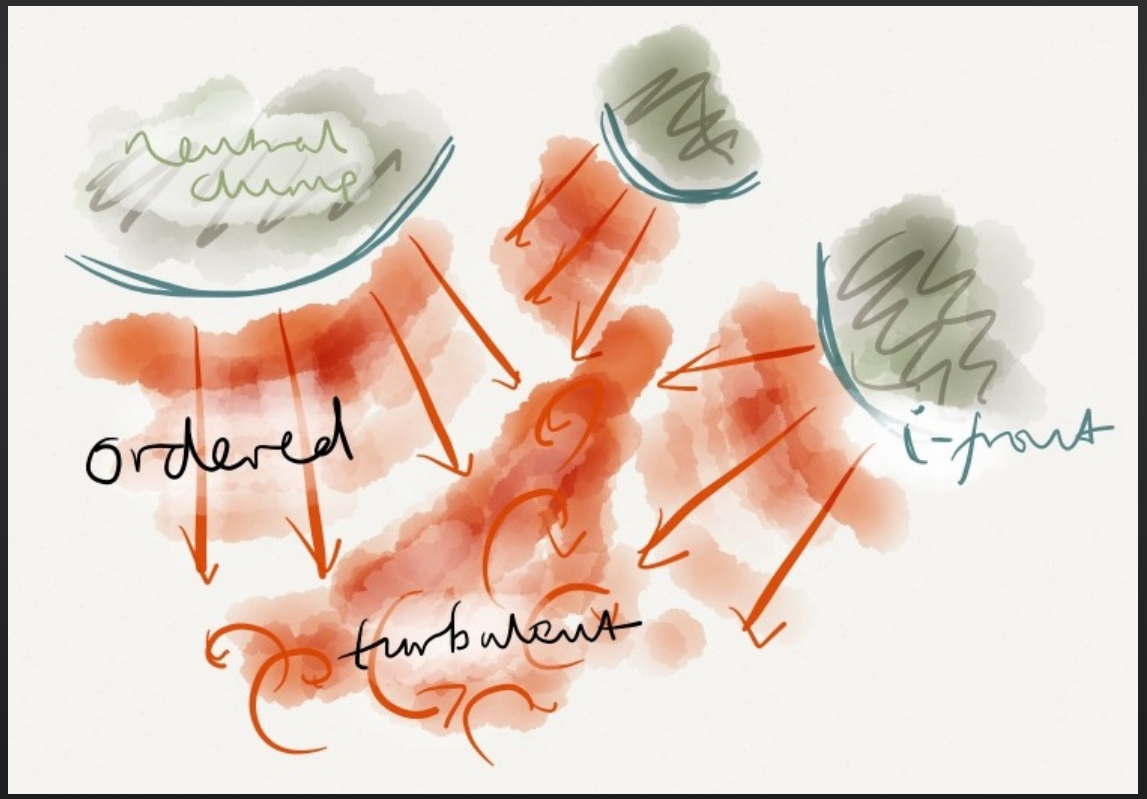
MIR Warm PAHs

Radio Free-free

Is anywhere safe from turbulence?

Yes!

Simulations show that 10–30% of the [O III] emission comes from the base of bright photoevaporation flows, where the velocity field is ordered.



Plan of the talk

Abundance fluctuations in H II regions and PNe

Mixing processes

Survival of metal-rich droplets in H II regions

Solid body evaporation in planetary nebulae

- Metal release during the PN phase
- Metal release during the AGB phase

Conclusions

Size and mass constraints

Destruction processes considered

- EUV photosputtering (stellar CSPN continuum)
- FUV photosputtering (Lyman α)
- Sputtering by ion impact
- Thermal sublimation

Size and mass constraints

The constraints that we find are very tight

- The solid bodies must be meter-size or larger
- The total mass of solid bodies must exceed a few hundredths of a solar mass for kilometer-sized bodies, scaling linearly with size
- This applies to volatile materials such as ices. For silicates, the constraints are tighter still

Size and mass constraints

Possible solid body populations:

Planets No . . . Minimum mass $\sim 1000\ M_\odot$!

Comets No . . . Mass of the Oort cloud $< 10^{-5}\ M_\odot$, but we need $\sim 0.03\ M_\odot$

Debris disks No . . . Mass $\sim 3 \times 10^{-6}\ M_\odot$ but for $a = 10\,\mathrm{m}$ we need $\sim 0.001\ M_\odot$

. . . but, what about the AGB phase?

The Asymptotic Giant Branch phase

- High luminosity – 10^3 to 10^4 $L_\odot$
- Unstable He- and H-burning shells – thermal pulses
- Strong mass loss – 10^{-7} $M_\odot$/year
- Duration $\sim 10^6$ years – much longer than PN phase

Could comets be *pre*-ablated?

- Photosphere is cool – only thermal sublimation

. . . but, what about the AGB phase?

Possible observational evidence

- H_2O emission from C-rich AGB star
- Melnick et al. (2001); Ford & Neufeld (2001)

However, you need a lot of comets around 100 AU

Solar System does not have them, but are we special?

- Late Heavy Bombardment
- Nice model

. . . but, what about the AGB phase?

. . . and you don't really have a megayear to do it

$$V_{\rm exp}({\rm PN}) < 6V_{\rm wind}({\rm AGB})$$

Most mass lost on AGB is never incorporated into PN

Finally, mixing would kill you

How can the evaporated metals be accelerated up to the AGB wind speed without also mixing them?

Plan of the talk

Abundance fluctuations in H II regions and PNe

Mixing processes

Survival of metal-rich droplets in H II regions

Solid body evaporation in planetary nebulae

Conclusions

Conclusions

H II regions

- Sub-milliparsec–sized, moderately metal-enriched droplets are a possible alternative explanation for observed t^2 and ADFs
- Turbulence efficiently destroys them, but they may survive long enough to contribute significantly to the observed spectrum.

Conclusions

Planetary nebulae

- Solid body destruction during the PN phase cannot explain posited abundance fluctuations in the ionized gas
  - The mass of the comet reservoir is unrealistically high
- But, comet sublimation during the AGB phase could work for stars with a comet population ten times more massive than the Sun's . . .
  - . . . so long as mixing is inefficient

The End

Thank you!