Search for turbulent hidden gas through interstellar scintillation

Where are the hidden atoms (the 4-0.5%)?

A new technique to measure the last unknown contribution to the baryonic hidden matter: cold H$_2$ (+He)

- Cold (10K) => no emission. Transparent medium.
- In the thick disk or/and in the halo
- Average column density toward LMC

- *Fractal structure*: covers ~1% of the sky.

Clumpuscules ~10 AU (Pfenniger & Combes 1994)

$250\text{g/m}^2 \leftrightarrow$ column of 3m H$_2$ (normal cond.)

~300m H$_2$ over 1% of the sky
These clumpuscules refract light

- Elementary process involved: **polarizability** $\alpha$
  - far from resonance
    $\Rightarrow$ classical forced oscillator formalism
  - close to initial propagation direction
    $\Rightarrow$ collective effect even with low molecular density $\sim 10^9 \text{ cm}^{-3} (<1/l^3)$

- Supplement of phase $\phi$ when crossing $\text{H}_2$ medium
  $\Rightarrow$ typically **80,000 x2p** (1% of the sky) @ $l=500\text{nm}$
Scintillation through a diffusive screen

Propagation of distorted wave surface driven by:
Fresnel diffraction + « global » refraction
Distance scales

4 distance scales characterize the speckle pattern

- **Diffusion radius** $R_{\text{diff}}$
  - separation such that: $s[f(r+R_{\text{diff}})-f(r)] = 1$ radian
  - Characterizes the turbulence
$R_{\text{diff}}$ : Statistical characterization of a stochastic screen

$R_{\text{diff}} = $ size of domain where $Df= 1 \text{ radian}$

or equivalently (@ $l = 500 \text{ nm}$)

$DN_l = 1.8 \times 10^{18} \text{ molecules/cm}^2$

- This corresponds to
  - $DN_l / N_l \sim 10^{-6}$
    for disk/halo clumpuscule
  - $DN_l / N_l \sim 10^{-4}$
    for Bok globule (NTT search)

\[
R_{\text{diff}} = 744 \text{ km} \times \left[ \frac{\lambda}{1 \mu m} \right]^{6/5} \left[ \frac{L_z}{10 \text{A.U.}} \right]^{-3/5} \left[ \frac{L_{\text{out}}}{10 \text{A.U.}} \right]^{2/5} \left[ \frac{\sigma_{3n}}{10^9 \text{cm}^{-3}} \right]^{-6/5}
\]

$L_z$ : Cloud size \hspace{1cm} $L_{\text{out}}$ : Turbulence outer scale
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- **Refraction radius** $R_{\text{ref}}$
  - diffractive spot of $R_{\text{diff}}$ patches $\sim z_0/l/R_{\text{diff}}$

- **Larger scale structures** of the diffusive gaz can play a role if focusing/defocusing configurations happen

- **Projected source size** $R_S$
  speckle from a pointlike source is convoluted by the source projected profile. $\rightarrow$ impacts the contrast of the illumination pattern
Simulation for a polychromatic extended source

Illumination in $K_s$ by a $K0V$ star@8kpc ($m_V=20.4$) through a cloud@160pc (B68) with $R_{\text{diff}}=150\text{km}$

$m = \frac{I}{I} = \text{modulation index}$
Time scale

If $R_{\text{ref}}$ is the largest scale:

$$t_{\text{ref}}(\lambda) = \frac{R_{\text{ref}}}{V_T} \sim 5.2 \text{ minutes} \left[ \frac{\lambda}{1 \mu m} \right] \left[ \frac{z_0}{1 \text{kpc}} \right] \left[ \frac{R_{\text{diff}}}{1000 \text{ km}} \right]^{-1} \left[ \frac{V_T}{100 \text{ km/s}} \right]^{-1}$$

Where

- $z_0$ is the distance to the cloud
- $V_T$ is the relative speed of the cloud with respect to the line of sight

$\Rightarrow V_T$ is also the speed of the illumination pattern in front of the telescope.
Modulation Index

Essentially depends on $R_S$ and $R_{\text{ref}}$
-> not on the details of the power spectrum of the fluctuations

$x = R_F^{1/3} \times R_{\text{ref}}^{5/6} \times R_S^{-7/6}$
Signature of scintillation

- **Stochastic light-curve** (not random)
  - Autocorrelation (power spectrum)
  - Characteristic time (few minutes)
  - Modulation index can be as high as 5%
    - decreases with star radius
    - depends on cloud structure

- **Signatures of a propagation effect**
  - Chromaticity (optical wavelengths)
    - Long time-scale variations (few min.) ~ achromatic
    - Short time-scale variations (sub-min.) varies with $l$
  - Correlation between light-curves measured by 2 telescopes decreases with their distance
Fore and backgrounds

- **Atmospheric turbulence: No impact**
  -> Prism effects, image dispersion
  -> BUT $\text{DI/I} < 1\%$ in a $>1m$ telescope
  **BECAUSE** atmospheric speckle with 3cm length scale is averaged in a $>1m$ aperture

Atmospheric speckle visible just before totality of a solar eclipse
Fore and backgrounds

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• **High altitude cirruses**
  - Would induce easy-to-detect *collective* effects on neighbour stars. But Scintillation by a 10AU object affects only one star.

• **« nearby » gas (at $\sim 10$pc)**
  - Scintillation would also occur on the biggest stars

• **Intrinsic variability**
  - Rare at this time scale and only with special stars (UV Ceti, flaring Wolf-Rayet)

Atmospheric speckle visible just before totality of a solar eclipse
Maximum fraction of LMC/SMC scintillating stars

\[ \Psi (m > m_{\text{threshold}}) = 10^{-2} \times f(m_{\text{threshold}}) \]

Where
- \( m \) is the modulation index
- \( f \) is the fraction of gas turbulent enough to have \( m > m_{\text{threshold}} \)

At maximum, 1% of the sky is covered by turbulent gas
Requirements to detect scintillation towards LMC

- Assuming $R_{\text{diff}} = 1000\text{km}$ (10 AU clumpuscules)
- $5\%$ modulation@500nm $\Rightarrow r_s < r_{A5} (10^5/\text{deg}^2)$

✓ Smaller than $A5$ type in LMC
✓ Characteristic time $\sim$ few min.
✓ Photometric precision required

$\Rightarrow M_V \sim 20.5$

$\Rightarrow$ sub-minute exposures $\sim 1\%$

✓ Dead-time $< \text{few sec.}$
✓ $B$ and $R$ partially correlated $\Rightarrow$
✓ Optical depth probably small

$\Rightarrow$ Telescope $> 2$ meters

Fast readout Camera

2 cameras

Wide field
Test towards Bok globule B68 and SMC
NTT IR (2 nights in june 2006)

Mainly test for background estimates and feasibility

- **B68 (& cb131, Circinus nebula)**
  - dust + **existing gas** at $z_0 \sim 80 \text{ pc}$
  - Column density $N_l \sim 2.6 \times 10^{22}\text{ cm}^{-2}$
  - Signal if $D N_l / N_l \sim 10^{-4}$ per 1000 km
  - 1114 stars monitored at $z_1 \sim 7 \text{ kpc}$
  - 50% are behind the nebula, 50% make a control sample
  - 2000 exposures of 10s in 2 nights

- **SMC**
  - blind search for **invisible bas**
  - 980 stars monitored at $z_1 \sim 64 \text{ kpc}$
  - 1000 exposures of 10s in 2 nights

- **Search for few % variability**
Results toward B68: A star scintillating through visible gas?
Results from feasibility studies: upper limits on scintillation optical depth

First fundamental result: **no overwhelming background**

Upper limits on scintillation probability => **constrain the turbulent gas abundance**

- **towards visible gas** (B68 and other nebulae)
- **towards invisible gas** (SMC)

\[ \tau(R_d) \sim 1\% \]

if halo only made of clumps

\[ \int \tau(R_d) dR_d \sim 1\% \]

\( R_d \sim 18 \text{ km} \) corresponds to densest clump (\( N_l^{\text{max}} \sim 10^{25} \text{ cm}^{-2} \))
Conclusions - perspectives

• Searching turbulent gas through scintillation is technically possible right now

• To discover scintillation effects, we need:
  – > 2m class telescope(s)
  – Wide field camera (visible) with fast readout
  – Start with 10-100 nights with microlensing networks
  – Preferably synchronized observations through 4m class telescopes to probe the best signature
    -> fluctuations are not correlated at large distance

• Technique sensitive to clumpuscules with structuration inducing column relative density fluctuations $\geq 10^{-7}$ ($10^{17}$ molecules/cm$^2$) per 1000km

• Long term (halo studies): GAIA, LSST

For the future…

A network of distant telescopes

• Would allow to decorrelate scintillation from interstellar clouds and atmospheric effects

• Snapshot of interferometric pattern + follow-up
  ✓ Simultaneous $R_{\text{diff}}$ and $V_T$ measurements
  ✓ $\Rightarrow$ positions and dynamics of the clouds
  ✓ Plus structuration of the clouds (inverse problem)
complements
Expected difficulties, cures

• **Blending** (crowded field) => differential photometry

• **Delicate analysis**
  – Detect and Subtract collective effects
  – Search for a not well defined signal
    • VIRGO robust filtering techniques (short duration signal)
    • Autocorrelation function (long duration signal)
    • *Time power spectrum*, essential tool for the inversion problem
      (as in radio-astronomy)

• **If interesting event** => complementary observations
  (large telescope photometry, spectroscopy, synchronized telescopes…)

Simulation: Fractal phase screen

- Kolmogorov turbulence -> realistic
- Other power laws under study, but small sensitivity expected
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This is a real storm cloud!
Atmosphere, atmosphere?

- Blurs PSF, but doesn’t affect the intensity collected by a large telescope
- ~5cm size speckle due to turbulent layers at ~10km
- Observable during total solar eclipses: «shadow bands»

Aperture dependence of the intensity variance (2 series of measurements)
Transparent molecular clouds
ISM turbulence and fractal dimension

Large cloud is gravitationally unstable, it fragments into smaller sub-clouds and produce a self-similar hierarchy structure.

Velocity dispersion vs. region size $r$ in composite clouds from Milky Way (Larson 1981)

Clouds are bound (virialized systems):

$\sigma_V^2 \sim \frac{\text{Mass}}{r} \Rightarrow \text{Mass} \sim r^D \Rightarrow \text{Fractal dimension}$

Turbulence kinetic energy spectrum (spatial frequencies):

$S(q_x, q_y, q_z) \sim q^{-\beta} \quad L_{\text{out}}^{-1} < q < L_{\text{in}}^{-1}$

$\beta = \frac{11}{3}$ Kolmogorov turbulence
Transparent molecular clouds
Building blocks of the fractal cloud

At some scale the cooling time equals the free-fall time and the fragmentation stops. These smallest cloudlets are called *clumpuscules*.

Pfenniger & Combes Model

At $T \sim 3$ K:

- Mass $\sim 0.8 - 2.3 \times 10^{-3} \ M_{\text{sun}}$
- Size $\sim 23 - 73$ A.U.
- Density $\sim 0.6 - 6 \times 10^9$ H$_2$ cm$^{-3}$
- Column density $\sim 0.8 - 2.7 \times 10^{24}$ H$_2$ cm$^{-2}$
- Free-fall time $\sim 1.2 - 3.9 \times 10^3$ year

Despite their short free-fall time, because of low temperature ($T < 10$ K) and the fractal structure ($1.6 < D < 2$)

- frequent collisions:
- no gravitational collapse

The turbulence energy transferred from galactic rotation to the hierarchy takes $\sim 3.7$ Gyr to dissipate through the structure.