Search for Turbulent Gas through Interstellar Scintillation

Marc Moniez, R. Ansari, F. Habibi, S. Rahvar

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Abstract Stars twinkle because their light propagates through the atmosphere. The same phenomenon is expected when the light of remote stars crosses a Galactic – disk or halo – refractive medium such as a molecular cloud. We present the promising results of a test performed with the ESO-NTT and the perspectives.

Key words: Galaxy:structure, dark matter, ISM

1 What is interstellar scintillation?

Refraction through an inhomogeneous transparent cloud (hereafter called screen) distorts the wave-front of incident electromagnetic waves (Fig.1) [Moniez (2003)]; For a *point-like* source, the intensity in the observer's plane is affected by interferences which, in the case of stochastic inhomogeneities, takes on the speckle aspect. At least 2 distance scales characterise this speckle:

- The diffusion radius $R_{diff}(\lambda)$ of the screen, defined as the transverse separation for which the root mean square of the phase difference at wavelength λ is 1 radian.
- The refraction radius

$$R_{ref}(\lambda) = \frac{\lambda z_0}{R_{diff}(\lambda)} \sim 30860\,km \left[\frac{\lambda}{1\,\mu m}\right] \left[\frac{z_0}{1\,kpc}\right] \left[\frac{R_{diff}(\lambda)}{1000\,km}\right]^{-1} \qquad (1)$$

  where z_0 is the distance to the screen. This is the size, in the observer's plane, of the diffraction spot from a patch of $R_{diff}(\lambda)$ in the screen's plane.

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After crossing a fractal cloud described by the Kolmogorov turbulence law (Fig. 1, left), the light from a *monochromatic point* source produces an illumination pattern on Earth made of speckles of size $R_{diff}(\lambda)$ within larger structures of size $R_{ref}(\lambda)$ (Fig. 1, right).

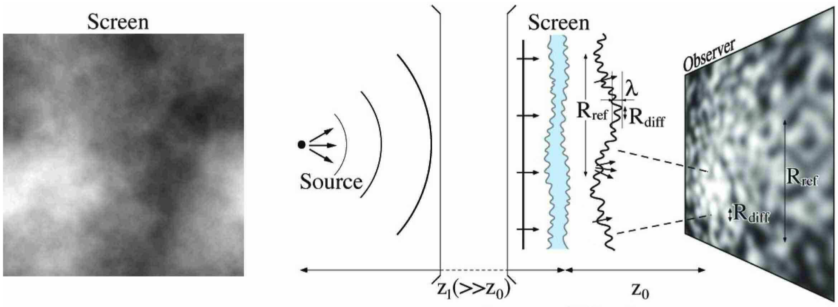


Fig. 1 *Left: a 2D stochastic phase screen (grey scale), from a simulation of gas affected by Kolmogorov-type turbulence.*
Right: the illumination pattern from a point source (left) after crossing such a phase screen. The distorted wavefront produces structures at scales $\sim R_{diff}(\lambda)$ *and* $R_{ref}(\lambda)$ *on the observer's plane.*

The illumination pattern from a stellar source of radius r_s is the convolution of the point-like intensity pattern with the projected intensity profile of the source (Fig. 2, up-right). The cloud, moving with transverse velocity V_T relative to the line of sight,

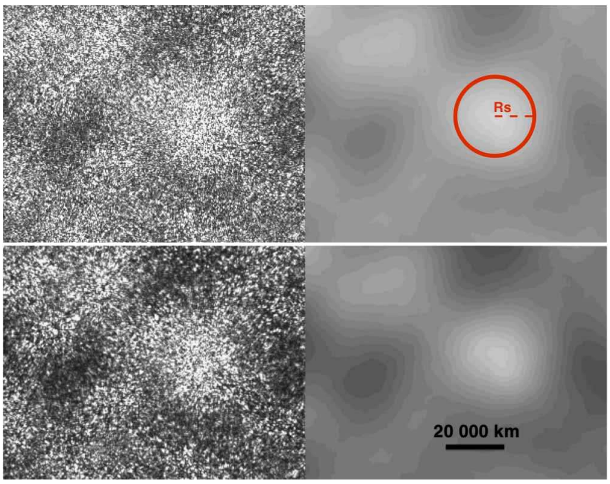


Fig. 2 *Simulated illumination map at* $\lambda = 2.16\mu m$ *on Earth from a point source (up-left)- and from a K0V star* ($r_s = 0.85R_\odot$, $M_V = 5.9$) *at* $z_1 = 8\,kpc$ *(right). The refracting cloud is assumed to be at* $z_0 = 160\,pc$ *with a turbulence parameter* $R_{diff}(2.16\mu m) = 150\,km$. *The circle shows the projection of the stellar disk* ($r_s \times z_0/z_1$). *The bottom maps are illuminations in the* K_s *wide band* ($\lambda_{central} = 2.162\mu m$, $\Delta\lambda = 0.275\mu m$).

will induce stochastic intensity fluctuations of the light received from the star at the characteristic time scale

$$t_{ref}(\lambda) = \frac{R_{ref}(\lambda)}{V_T} \sim 5.2\,minutes \left[\frac{\lambda}{1\mu m}\right] \left[\frac{z_0}{1\,kpc}\right] \left[\frac{R_{diff}(\lambda)}{1000\,km}\right]^{-1} \left[\frac{V_T}{100\,km/s}\right]^{-1}. \quad (2)$$

with modulation index $m_{scint.} = \sigma_I/\bar{I}$ given by

$$m_{scint.} = 0.12 \left[\frac{\lambda}{1\mu m}\right] \left[\frac{z_0}{10pc}\right]^{-1/6} \left[\frac{R_{diff}(\lambda)}{1000km}\right]^{-5/6} \left[\frac{r_s/z_1}{R_\odot/10kpc}\right]^{-7/6}. \quad (3)$$

This modulation index decreases when the apparent stellar radius increases.

Signature of the scintillation signal: The first two signatures point to a propagation effect, which is incompatible with any type of intrinsic source variability.

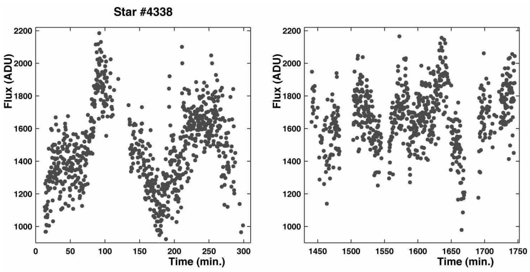
- Chromaticity: Since R_{ref} varies with $\lambda^{-1/5}$, one expects a small variation of the characteristic time scale $t_{ref}(\lambda)$ between the red side of the optical spectrum and the blue side.
- Spatial decorrelation: We expect a decorrelation between the light-curves observed at different telescope sites, increasing with their distance.
- Correlation between the stellar radius and the modulation index: Big stars scintillate less than small stars through the same gaseous structure.
- Location: The probability for scintillation is correlated with the foreground gas column-density. Therefore, extended structures may induce scintillation of apparently neighboring stars looking like clusters.

Foreground effects, background to the signal: Atmospheric *intensity* scintillation is negligible through a large telescope [Dravins et al. (1998)]. Any other atmospheric effect should be easy to recognize as it affects all stars. Asterosismology, granularity of the stellar surface, spots or eruptions produce variations of very different amplitudes and time scales. A rare type of recurrent variable stars exhibit emission variations at the minute scale, but such objects could be identified from their spectrum.

2 Preliminary studies with the NTT

During two nights of June 2006, 4749 consecutive exposures of $T_{exp} = 10\,s$ have been taken with the infra-red SOFI detector in K_s and J through nebulae B68, cb131, Circinus and towards SMC [Habibi et al. (2011)]. A candidate has been found towards B68 (Fig. 3), but the poor photometric precision in K_s and other limitations prevent us from definitive conclusions. Nevertheless, we can conclude from the rarity of stochastically fluctuating objects that there is no significant population of stars that can mimic scintillation effects, and future searches should not be overwhelmed by background of fakes.

From the observed SMC light-curves we also established upper limits on invisible gaseous structures as a function of their diffusion radius (Fig. 4). This limit, although not really competitive, already excludes a major contribution of strongly



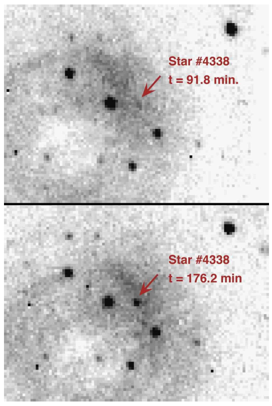


Fig. 3 *Light-curves for the two nights of observation (above) and images of the candidate found toward B68 during a low-luminosity phase (up-right) and a high-luminosity phase (bottom); North is up, East is left.*

turbulent gas to the hidden Galactic matter. These constaints are at the moment limited by the statistics and by the photometric precision.

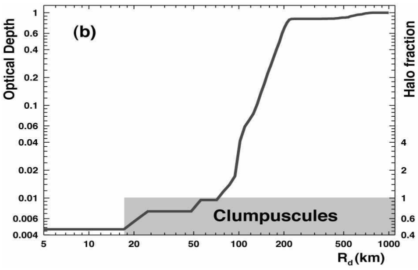


Fig. 4 *The 95%CL maximum optical depth of structures with* $R_{diff}(1.25\mu m) < R_d$ *toward the SMC. The right scale gives the maximum contribution of structures with* $R_{diff}(1.25\mu m) < R_d$ *to the Galactic halo (in fraction); the gray zone shows the possible region for the hidden gas clumpuscules expected from the model of [Pfenniger & Combes (1994)].*

3 Perspectives

LSST will be an ideal setup to search for this signature of gas thanks to the fast readout and to the wide and deep field. Scintillation signal would provide a new tool to measure the inhomogeneities and the dynamics of nebulae, and to probe the molecular hydrogen contribution to the Milky-Way baryonic hidden matter.

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