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Search for Hidden Turbulent Gas through Interstellar Scintillation

Moniez M.,[1] Ansari R.,[1] Habibi F.,[2] and Rahvar S. [3]

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[1]Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS, Université de Paris-Sud, B.P. 34, 91898 Orsay Cedex, France

[2]School of Astronomy, Institute for Research in Fundamental Sciences (IPM), PO Box 19395-5531,Tehran, Iran

[3]Department of Physics, Sharif University of Technology PO Box 11365-9161, Tehran, Iran and Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, Ontario N2L 2y5, Canada

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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 of detection.

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. Two distance scales characterise this speckle:

- The diffraction 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 $R_{ref}(\lambda) = \lambda z_0 / R_{diff}(\lambda)$ 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.

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)[Habibi et al. 2013]. The illumination pattern from a stellar source of radius r_s is much less contrasted, since it is the convolution of the point-source intensity pattern with the projected intensity profile of the source (Fig. 2, right). The cloud, moving with transverse velocity V_T relative to the line of sight, induces stochastic intensity fluctuations of the illumination at a given point with the characteristic time scale

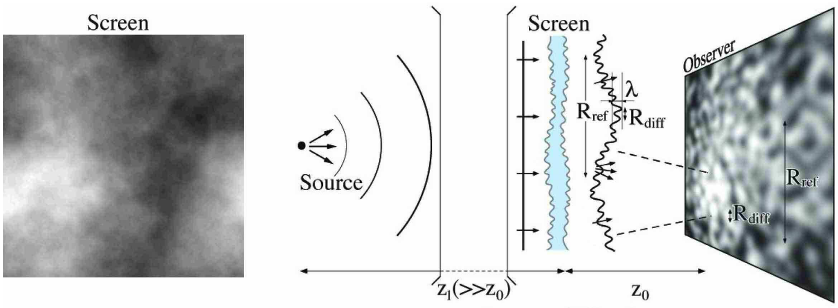

Figure 1: *Left: a 2D stochastic phase screen (grey scale), from a simulation of gas affected by Kolmogorov-type turbulence. Right: the illumination pattern from a point source (left) after crossing the phase screen. Distorted wavefront produces structures at scales* $\sim R_{diff}(\lambda)$ *and* $R_{ref}(\lambda)$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

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

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

$$m_{scint.} = 0.035 \left[\frac{\lambda}{1\mu m}\right] \left[\frac{z_0}{1Kpc}\right]^{-1/6} \left[\frac{R_{diff}(\lambda)}{1000km}\right]^{-5/6} \left[\frac{r_s/z_1}{R_\odot/10kpc}\right]^{-7/6}. \tag{2}$$

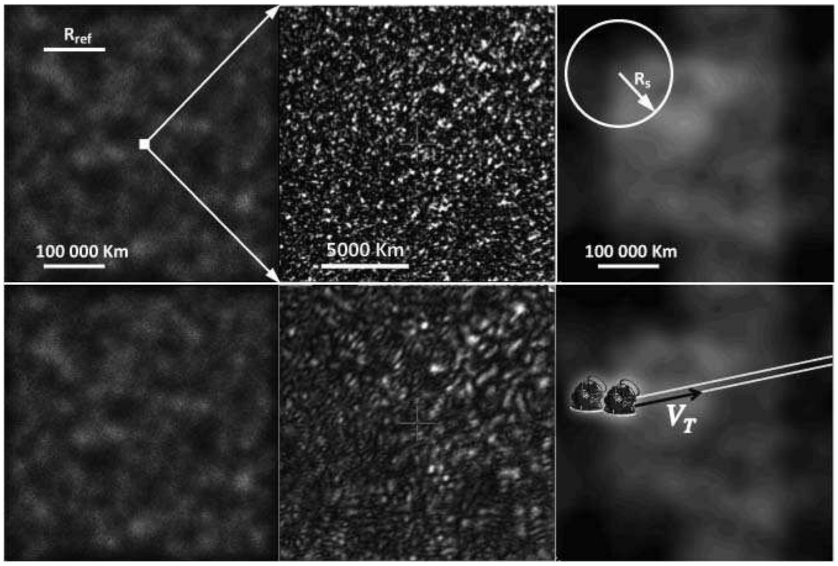

Figure 2: *Simulated illumination maps at* $\lambda = 2.16\mu m$ *on Earth from a point source (up-left)- and from a K0V star (*$r_s = 0.85 R_\odot$*,* $M_V = 5.9$*) at* $z_0 + z_1 = 1.16\,kpc$ *(right). The refracting cloud is assumed to be at* $z_0 = 160\,pc$ *with* $R_{diff}(2.16\mu m) = 100\,km$*. 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 *band (*$\lambda_{central} = 2.162\mu m$*,* $\Delta\lambda = 0.275\mu m$*).*

Signature of the scintillation signal: In addition to the stochasticity, the time scale and scintillation index, several specificities characterise a scintillation signal.

- Chromaticity: We expect 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: Extended gas structures should induce (decorrelated) scintillation of apparently neighboring stars.

The first two signatures are probably the strongest ones, since they point to a propagation effect, which is incompatible with any type of intrinsic source variability.

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 is a collective effect. 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.

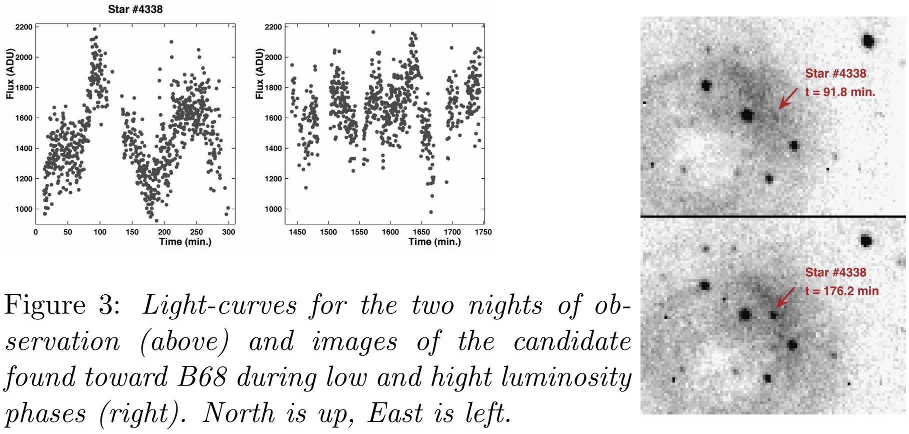

Figure 3: *Light-curves for the two nights of observation (above) and images of the candidate found toward B68 during low and hight luminosity phases (right). North is up, East is left.*

From the observed SMC light-curves we also established upper limits on invisible gaseous structures as a function of their diffraction radius (Fig.

4). This limit, although not really competitive, already excludes a major contribution of strongly turbulent gas to the hidden Galactic matter. These constraints are currently limited by the statistics and by the photometric precision.

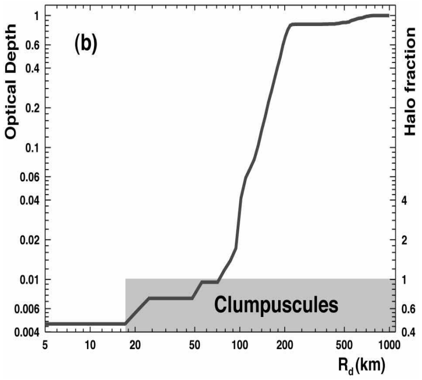

Figure 4: *The* $95\% CL$ *maximum optical depth of structures with* $R_{diff}(1.25\mu m) < R_d$ *toward the SMC. The right scale gives the maximum contribution of structures with* $R_{diff}(1.25\mu m) < R_d$ *to the Galactic halo (in fraction); the gray zone shows the possible region for the hidden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

3 Perspectives

Fig. 5 allows one to estimate the sensitivity to turbulent gas when knowing the photometric performances of an observation system, assuming that the light-curve sampling is sufficient to observe the time structure ($\Delta t_{sampling} \ll t_{ref}$). LSST will be an ideal setup for such a search 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.

References

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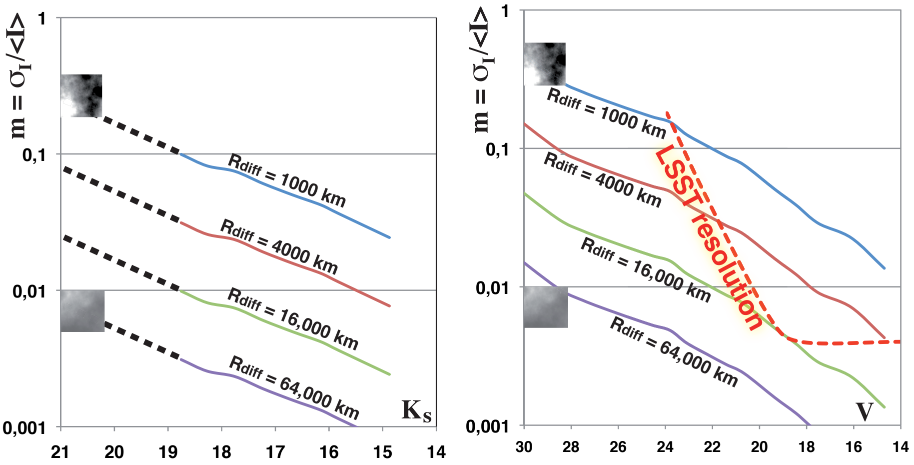

Figure 5: *The expected modulation index* **m** *as a function of the source apparent magnitude, for 4 different values of* R_{diff}.
LEFT: Screen (B68) at $z_0 = 160pc$*, source at* $z_1 = 7Kpc$*, observed in* K_s *band.*
RIGHT: Screen (invisible halo clumpuscule) at $z_0 = 1Kpc$*, source at* $z_1 = 55Kpc$ *(within LMC), observed in* **V**. *The configurations above the LSST photometric uncertainty curve (15s exposures) would produce detectable scintillation.*

[Pfenniger & Combes 1994] Pfenniger, D. & Combes, F. (1994) A&A 285, 94.