6 SUMMARY AND SPECULATION

We have used statistical analysis of high-resolution spectroscopic observations of optical emission lines in the central 0.4×0.6 pc of the Orion Nebula in order to characterize the turbulence in the ionized gas. The analysis has been guided and informed by radiation hydrodynamic simulations of H II region evolution. The techniques that we have applied are:

(i) Second order structure function of velocity centroids, which gives the variation as a function of plane-of-sky separation of the average velocity integrated along the line of sight.
(ii) Velocity channel analysis (VCA), which compares the spatial power spectrum slope of velocity-resolved and velocity-integrated emission profiles of the same line.
(iii) Line width analysis, which is sensitive to velocity fluctuations along the line of sight
(iv) Probability density function (PDF) of the surface brightness in different lines

Our principal empirical findings are as follows:

(i) The VCA technique is the most reliable means of determining the spectrum of velocity fluctuations in the ionized gas, and we find consistent evidence from both low and high ionization lines for a Kolmogorov-type spectrum ($\delta u \sim l^{1/3}$) for length scales, l, between 0.05 pc ($\approx 22''$) and 0.02 pc ($\approx 8''$). Unfortunately, VCA can not be applied if the thermal or instrumental line width is larger than the velocity differences of interest, which rules out its application to the Hα line and to scales smaller than 0.02 pc.
(ii) The structure functions show systematic trends with degree of ionization. Higher ionization lines tend to show larger autocorrelation scales, larger total plane-of-sky velocity dispersions, and steeper slopes than lower ionization lines. The changes in slopes are difficult to interpret because of the influence of projection smearing and sensitivity to details of the observational methodology.
(iii) The characteristic length of 0.05 pc is special in at least two ways, corresponding to both the autocorrelation scale of velocity differences for low-ionization lines and also a break in the power spectrum of surface brightness fluctuations in all lines. We suggest that this is the dominant scale for density fluctuations in the nebula and is also the main driving scale of the turbulence. A further break in the surface brightness power spectra occurs at the smaller scale of 0.02 pc ($\approx 8''$), but there is no obvious feature in the structure functions at this scale.
(iv) There are three lines of evidence suggesting that the velocity fluctuations are not homogeneous on the largest scales, but rather that the turbulent conditions themselves vary, both across the sky and along the line of sight, on scales larger than the velocity autocorrelation length of 0.05–0.15 pc:

(a) The structure function slope of the [N II] line is significantly steeper in the southern half of our observed field than in the northern half
(b) The plane-of-sky velocity dispersion increases with increasing ionization, implying an increasing amplitude of fluctuations towards the interior of the nebula
(c) The line-of-sight non-thermal velocity dispersion (after removing the confounding effect of dust scattering) is typically twice as large (≈ 6 km s^{-1}) as the plane-of-sky velocity dispersion (≈ 6 km s^{-1}). In order to explain this ratio in terms of a homogeneous turbulent layer, the line-of-sight depth of the layer would need to be at least 10 times the velocity autocorrelation length, which is unrealistically large. Instead, the result is more naturally explained by large-scale velocity gradients (such as radial expansion), combined with emissivity fluctuations along the line of sight.

(v) The PDF of surface brightness fluctuations is approximately log-normal with a fractional width of 0.4–0.5 in all lines. The amplitude of these fluctuations is marginally consistent with their having being wholly caused by the observed velocity fluctuations, so long as the velocity field is irrotational at the driving scale.
(vi) The ordered component of the velocity dispersion can be estimated to be ≈ 4.5 km s^{-1}, which implies that the turbulent component is of roughly similar magnitude so that their quadrature sum gives the observed total dispersion of 6 km s^{-1}.

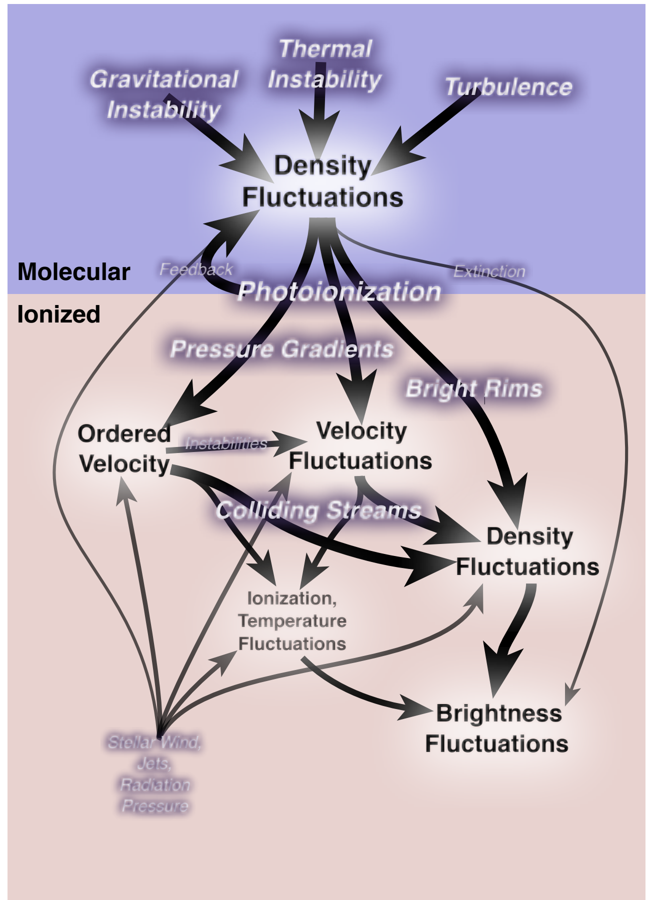

Figure 1. Causal relationships (arrows) between different types of fluctuations (black text) in molecular clouds (above) and H II regions (below) via different physical processes (white text). Line thickness and text size is proportional to the relative importance of each process in the Orion Nebula.

Finally, we offer a speculative account of the complex web of physical processes that give rise to to the velocity and brightness fluctuations that we observe in the Orion Nebula. This is illustrated in Figure 1, where the most important causal links are shown by thick arrows and secondary processes by thin arrows.

The principal origin of all structure in the H II region is the highly filamentary and clumpy density structure in the molecular cloud from which it is emerging, which in turn has its origin in some combination of thermal and gravitational instability and supersonic turbulence (Padoan & Nordlund 2002; **?**). In the molecular gas, thermal pressure is negligible compared with magnetic pressure, turbulent ram pressure, and the gravitational potential. However, the large temperature increase that accompanies photoionization means that thermal pressure dominates in the H II region, so that density gradients are converted into pressure gradients that can accelerate the gas. The fractal nature of the molecular density means that gas acceleration occurs on multiple scales, from the global outward radial expansion of the H II region (which in Orion is a highly one-sided champagne flow) down to photoevaporation flows from individual globules. One piece of evidence for a direct connection between molecular density fluctuations and ionized velocity fluctuations is that Kainulainen et al. (2016) find correlation lengths of order 0.08 pc for the separations of molecular cores along the ridge that lies behind the Orion Nebula, which is similar to the correlation lengths we find for the velocity fluctuations in the nebula.

Ionized density fluctuations can arise directly from the molecular density fluctuations, such as the bright rims at the edges of photoionized globules (Henney et al. 2009), and this is most important in the lower ionization zones near the ionization front where the [S II] and [N II] emission is strong. In the more highly ionized interior of the nebula, it is collisions between opposing velocity streams that produce the ionized density fluctuations, but these fluctuations are less extreme than those seen in molecular gas because the turbulence is subsonic.

The ionized density fluctuations are the primary determinant of the emission line surface brightness fluctuations (§ 4.5), although ionization and temperature structure can make a contribution for particular lines and there is also a direct contribution from foreground molecular density fluctuations via dust extinction (O'Dell & Yusef-Zadeh 2000).

Finally, a variety of other processes, such as O star winds, radiation pressure, and bipolar jets from young stars can play a secondary role in stirring up gas motions. In the case of the Orion Nebula, evidence for the influence of stellar wind interactions is restricted to the central 0.05 pc (García-Arredondo et al. 2001) and the low-density western outskirts (Güdel et al. 2008), and they seem to have little influence on the bulk of the nebular gas. Stellar wind effects are more important in older and more massive regions that contain LBV and Wolf-Rayet stars (e.g., Smith et al. 2007). Similarly, radiation pressure, although unimportant in Orion, becomes much more important in higher luminosity regions (Krumholz & Matzner 2009). Herbig-Haro jets and bowshocks dominate the far wings ($\delta u \sim 50$ km s^{-1}) of the velocity distribution in Orion (Henney et al. 2007), but the total kinetic energy of these high velocity flows is relatively low, so that the effect on the global velocity statistics is minor.

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