Snakes in the Plane:
Characteristic Clump Spacing in Phil-amentary Infrared Dark Clouds

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Philosophy

24 x 24 Actual Grid Used

LISPI Star Counts Red Plate

The dot is at
\[ \alpha = 4^h 30^m 00^s \\
\beta = 18^\circ 6' 6" \]

66"/mm

X = 4.5
Y = 12.5
Infrared Dark Clouds

- Clouds that exhibit significant mid-IR opacity
- Extreme properties
  - Cold (<15 K)
  - Dense (>10^4 cm^-3)
  - Enormous column densities (>10^{23} cm^-2)
- Most are extremely filamentary

GLIMPSE 8 \(\mu\)m image

Perault et al. 1996; Egan et al. 1998; Carey et al. 1998, 2000; Hennebelle et al. 2001
Sizes and Masses of IRDCs
- Typical size **few pc**
- Typical mass **few 1000 \(M_\odot\)**

Comparable to warm, high-mass star-forming molecular clumps:
- Orion Trapezium (2 pc, 4500 \(M_\odot\))
- Ophiuchus (2 pc, 600 \(M_\odot\))

But IRDCs are colder and with little obvious star formation.

**IRDCs host the earliest stages of high-mass star formation.**

Carey et al. 1998; Egan et al. 1998; Redman et al. 2003; Pillai et al. 2006; Simon et al. 2006b; Rathborne et al. 2006; Wang et al. 2008; Ragan et al. 2009
IRDCs in 1.2 mm continuum:
IRAM 30 m/MAMBO bolometer array

Thermal emission at 1.2 mm from cold dust reveals internal structures.

IRDCs contain compact cores:

Sizes $< 0.5$ pc

Masses $\sim 120$ $M_{\odot}$

These properties are exactly what we expect for cores that will give rise to high-mass protostars (and protoclusters).

Rathborne et al. 2006
About 1/3 of IRDC cores have enhanced 4.5 µm emission and 24 µm point sources.

The combination of IRAC “green fuzzies” and 24 µm point sources suggests that some IRDC cores are actively forming stars. We call these “active cores.” Those without we call “quiescent.”

Chambers et al. 2009; also Beuther & Steinacker 2007
The presence of a hot core in an IRDC establishes an important link between IRDCs and the early phases of high-mass star formation.

Rathborne et al. 2008
IRDCs are the birthplaces of high-mass stars

- IRDCs match the size and mass of high-mass star-forming molecular clumps.
- IRDCs are located preferentially in spiral arms.
- IRDCs contain cores that match the size and mass of high-mass pre-stellar and protostellar (protocluster) cores.
- Active IRDC cores unambiguously contain high-mass protostars.

The Nessie Nebula:
An extremely Phil-amentary IRDC

Size > 150 pc x 0.5 pc
Aspects ratio > 300:1 !

Blue - 3.6µm, Green - 8µm, Red - 24µm

Image credit: NASA/JPL-Caltech/Univ. of Wisconsin
ATNF Mopra HNC 1-0 map: Cold, dense molecular gas matches mid-IR extinction

Blue - 3.6µm, Green - 8µm, Red - 24µm

Image credit: NASA/JPL-Caltech/Univ. of Wisconsin
Velocities across the filament are the same: Nessie is one coherent object

Kinematic Distance = 3.2 kpc
Clumps have a characteristic separation of \(~6\text{ pc}\), or \(~11\text{ times thickness}\).
Molecular gas matches mid-IR extinction

ATNF Mopra

HNC 1-0, $V = -38$ to $-42$ km/s

We find that, for most IRDCs, HNC is the brightest $\sim 90$ GHz line due to the chemistry of very cold gas.

See also Pillai et al. 2007 for deuteration studies.
“Varicose” or “Sausage” Instability

When a column of fluid has a restoring force it pinches off into beads.
Self-gravitating fluid cylinder

Chandrasekhar and Fermi (1953) analyzed the stability of a self-gravitating cylindrical fluid of radius $R$ and density $\rho$.

Only axisymmetric “m=0” modes are unstable. All perturbations along the z-axis with a wavelength larger than a critical wavelength are unstable to the varicose instability

\[
\lambda_c = \frac{2\pi R}{1.0668} = 5.9R
\]
Self-gravitating fluid cylinder

The fastest growing mode has a wavelength

\[ \lambda_{\text{max}} = \frac{2\pi R}{0.580} \approx 11R \]

Blobs will tend to form with this spacing.

Formation time for blobs is

\[ \tau_{\text{pinch}} = \frac{1}{0.2455 \sqrt{4\pi G \rho}} \approx 2\tau_{\text{free-fall}} \]

e.g., Chandrasekhar and Fermi 1953; Nagasawa 1987; Tomisaka 1995
Apply to Nessie

Assume $n = 10^4$ cm$^{-3}$, $R = 0.5$ pc

Spacing between blobs should be $\lambda_{\text{max}} = 11R$ or $\sim 5.5$ pc

Time for blob formation is $t \sim 8 \times 10^5$ yr.

For comparison $\lambda_{\text{Jeans}} \sim 0.1$ pc
Linear mass density (mass/length)

Critical linear mass density for a self-gravitating cylindrical fluid:

\[ \mu = \frac{M}{l} = \frac{2\sigma^2}{G} \]

For \( \Delta v = 2.5 \text{ km/s} \), \( \mu = 525 \text{ M}_{\odot}/\text{pc} \), in excellent agreement with Nessie (and other filaments like Orion).
Speculation: All High-Mass stars began their lives in filamentary IRDCs

Most known high-mass star forming regions are associated with filamentary structures, e.g. Orion

Tatematsu, Kandori, Umemoto, Sekimoto 2008
Evolution of IRDCs

1. Formation of filamentary structure
1. Fragmentation into pre-stellar cores via varicose fluid instability
3. Formation of high-mass protostars
4. Formation of ionized bubbles
5. Disruption and cluster emergence
Early stage: the Snake
Early Stage: Nessie
Later stage: IRDC 43
Latest stages: NGC 6334
Latest stages: NGC 6334
Latest Stages: NGC 6334

GLIMPSE 8 µm
Implications of Phil-amentary Star-formation

- The sizes, masses, and spacing of cores (and clusters) may be controlled primarily by the varicose fluid instability in a self-gravitating, filamentary fluid.
- Accretion onto cores could be anisotropic.
- The evolution of high-mass protostars and H II regions could be heavily influenced by filamentary geometry.