Deflection of a Protostellar Outflow: The Bent Story of NGC 1333 IRAS 4A

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Minho Choi

Evolutionary Scenario of Low-Mass Young Stellar Objects

- Classification
  - Spectral Energy Distribution
  - Class 0 \rightarrow I \rightarrow II \rightarrow III
- Class 0: Protostar
  - Main accretion phase
  - Energetic outflows
- Class I: Protostar
  - Visible in near-IR
- Class II: Pre-main seq. star
  - Classical T Tauri stars
- Class III: Pre-main seq. star
  - Weak-emission T Tauri stars

Driving Source

IRAS 4A Protobinary System

NGC 1333 Cluster Forming Region

- "Burst" of star forming activities: numerous outflows and Class 0/I sources

NGC 1333 IRAS 4 Multiple System

- NGC 1333 cloud (d ~ 320 pc)
  - Contains a cluster of sub-mm sources.
- IRAS 4
  - Contains multiple Class 0 sources.
  - One of the brightest (low-mass) Class 0 sources in the sky.

IRAS 4A Protobinary System

- IRAS 4A was resolved into a protobinary system with a \sim 1.7" separation: A1 and A2.
**NGC 1333 IRAS 4A Outflow System**

**Effects of Angular Resolution and Outflow Tracers**

*Large-scale images of H$_2$/CO show that IRAS 4A drives an extremely well-collimated outflow in the NE-SW direction.*

*CS outflow map shows a short outflow near IRAS 4A flowing in the N-S direction.*

*Directional variability: intrinsic to the outflow engine?*

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**Interferometric Images**

- **HCN 1-0 map**
  - There are at least two outflows.
  - Wigging outflow?
  - Difficult to study kinematics

- **CO 2-1 map:** Magnetic deflection of the NE lobe?

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**The Best Tracer of the Outflow Shear Zone: SiO**

- Most of the SiO emission comes away from the ambient cloud velocity.
- Single-dish map of high-velocity SiO emission shows well-collimated outflows.

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**Interferometric SiO Map**

**High-resolution Imaging in the Best Outflow Tracer**

*Clearer Picture (and More Questions)*

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**VLA SiO 1-0 Map**

- Unprecedented details revealed.
- The main (NE-SW) outflow is extremely well-collimated.
- There is a sharp bend in the middle of the NE lobe.
- Synthesized beam = 2"
Deflection of the NE Jet

- NE/SW lobes are asymmetric.
- NE lobe: complicated kinematics.

Deflection of the NE Outflow

- External perturbation (not intrinsic variability)
  - Asymmetric morphology
  - NE lobe shows complicated kinematics.
  - The downstream (deflected) segment is brighter than the upstream segment.
- Perturbation models
  - Jet-core collision or magnetic deflection?
  - Magnetic deflection is unlikely.
    - Magnetic deflection requires unrealistically strong fields (~1 mG).
    - Magnetically deflected flow should lose collimation very quickly.
  - Collision with a dense core is more plausible.

Magnetic Deflection of YSO Outflow

- Low-velocity component can be deflected by modest fields, but high-velocity component needs very strong fields to be deflected.
  - Each component deflected at a different angle -> decollimation
  - Highly asymmetric cocoon
- Magnetic fields are distorted and compressed at the jet head.

Jet-Core Collision

- YSO jets can be deflected by modestly dense (>10^3 cm^-3) molecular cores.
- Deflected flow follows the “surface” of the core and may appear well-collimated.
  - However, simulations were done assuming idealized conditions.

Reality Check

- The 8 km/s component of the ambient cloud is located to the north of the bending point.
- Opening angle
  - Prediction: 7-21 deg
  - Measurement: 6-25 deg (projected angle)
- Timescale
  - Assuming a jet proper motion of 80-250 km/s, deflection age is 100-300 yr.
- Jet-core collision model is consistent with the observations.

The Interacting Region

- BIMA HCN 1-0 map shows an emission peak located 1.5” north of the bending point.
- The HCN emission structure is elongated parallel to the deflected SiO flow with a 2” offset.
- The HCN peak is probably the jet-core interaction region on the “surface” of the core, not the density peak of the core itself.
The Obstructing Core

- BIMA map suggests the existence of a dense core to the north of the bending point, but most of the flux were resolved out.
- Combination of the BIMA and the 12 m data shows the location of the obstructing core at a correct flux scale.
- The NE jet is making a nearly head-on collision to a dense core.
- Density ~ $10^5$ cm$^{-3}$ – High enough to deflect a protostellar jet

Implications

- Ambient cloud is not a passive medium. Dense cores may play an important role in shaping protostellar outflows.
- Energy/momentum injection
  - IRAS 4A NE outflow: Deflection angle ~ 34 deg (projected)
  - The incident jet may be losing a significant fraction (~30%) of the kinetic energy through the collision process.
- Cloud support and large-scale structure
  - If outflow plays an important role in cloud support, energy/momentum should be transferred before exiting ambient cloud. The jet-core collision may increase the efficiency of energy transfer.
  - The jet-core collision mechanism may work better in cluster forming clouds than in isolated cores or globules.
- Outflows also affect the chemistry of ambient clouds.

Summary

- The NGC 1333 IRAS 4A outflow system was imaged in the SiO v=0 J=1-0 line with a 2" resolution using VLA.
- The main bipolar outflow (NE-SW) is extremely well-collimated.
- There is a sharp bend in the middle of the NE outflow lobe, but not in the SW lobe.
- Several lines of evidence suggest that the NE flow was deflected as a result of a jet-core collision.
- The obstructing core was imaged in the HCO+/HCN lines using BIMA + NRAO 12 m telescopes.
Jet-Core Collision
- The jet drills a cavity and may choke off, and the obstructing core may be destroyed.
  - Deflection is a transient phenomenon.
  - Deflection timescale ~ 100 - 10000 yr
  - Timescale can be longer if the jet is non-steady or if the obstructing core contains magnetic fields.
- Decollimation
  - Opening angle depends on the jet velocity and the deflection angle.

Drifting Axis of the IRAS 4A Outflow
- The (unperturbed) SW outflow shows a gentle curve.
  - The base and outer tip of the NE outflow is in the reverse direction of the SW outflow.
- Intrinsic variability: The IRAS 4A outflow axis is drifting (rotating) clockwise in the plane of the sky.
  - Axis drift rate = 0.011 deg/yr
- The large deflection angle of the NE flow can be maintained for a long time because the incident flow is non-steady.