The spine of the swan: a Herschel study of the DR21 ridge and filaments in Cygnus X

How to cite:

For guidance on citations see FAQs.

© 2012 ESO

Version: Version of Record

Link(s) to article on publisher’s website:
http://dx.doi.org/doi:10.1051/0004-6361/201219429

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online’s data policy on reuse of materials please consult the policies page.
The spine of the swan: a Herschel* study of the DR21 ridge and filaments in Cygnus X**

M. Hennemann¹, F. Motte¹, N. Schneider¹, P. Didelon¹, T. Hill¹, D. Arzoumanian¹, S. Bontemps²,³, T. Csengeri⁴, Ph. André⁴, V. Konyves⁵, F. Louvet¹, A. Marston⁶, A. Men'shchikov⁷, V. Minier⁵, Q. Nguyen Luong⁶,⁷, P. Palmeirim¹, N. Peretto¹, M. Sauvage¹, A. Zavagno⁷, L. D. Anderson⁸, J.-Ph. Bernard⁹, J. Di Francesco¹⁰, D. Elia¹¹, J. Z. Li¹², P. G. Martin⁶, S. Molinari¹¹, S. Pezzuto¹¹, D. Russeil⁷, K. L. J. Rygl¹¹, E. Schisano¹¹, L. Spinoglio¹¹, T. Soubie¹³, D. Ward-Thompson¹⁴, and G. J. White¹⁵,¹⁶

¹ AIM Paris-Saclay, CEA/DSM/IRFU – CNRS/INSU – Université Paris Diderot, CEA Saclay, 91919 Gif-sur-Yvette Cedex, France
e-mail: martin.hennemann@cea.fr

² Université de Bordeaux, LAB, UMR5804, 33270 Floirac, France

³ CNRS, LAB, UMR5804, 33270 Floirac, France

⁴ Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

⁵ Herschel Science Centre, ESAC, ESA, PO Box 78, Villanueva de la Cañada, 28691 Madrid, Spain

⁶ Canadian Institute for Theoretical Astrophysics – CITA, University of Toronto, 60 St. George Street, Toronto, Ontario, MSS 3HB, Canada

⁷ Laboratoire d’Astrophysique de Marseille, CNRS/INSU – Université de Provence, 13388 Marseille Cedex 13, France

⁸ Department of Physics, West Virginia University, Morgantown, WV 26506, USA

⁹ IRAP, CNRS (UMR 5277), Université Paul Sabatier, 9 avenue du Colonel Roche, 31028 Toulouse Cedex 4, France

¹⁰ National Research Council of Canada, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada

¹¹ Istituto di Astrofisica e Planetologia Spaziali – IAPS, Istituto Nazionale di Astrofisica – INAF, via Fosso del Cavaliere 100, 00133 Roma, Italy

¹² National Astronomical Observatories, Chinese Academy of Sciences, A20 Datun Road, Chaoyang District, 100012 Beijing, PR China

¹³ Institut d’Astrophysique de Paris, Université Pierre et Marie Curie (UPMC), CNRS UMR 7095, 75014 Paris, France

¹⁴ Jeremiah Horrocks Institute, University of Central Lancashire, Preston PR1 2HE, UK

¹⁵ Department of Physics & Astronomy, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK

¹⁶ Space Science & Technology Department, CCLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK

Received 17 April 2012 / Accepted 5 June 2012

ABSTRACT

In order to characterise the cloud structures responsible for the formation of high-mass stars, we present Herschel observations of the DR21 environment. Maps of the column density and dust temperature unveil the structure of the DR21 ridge and several connected filaments. The ridge has column densities higher than $10^{23} \text{ cm}^{-2}$ over a region of 2.3 pc$^2$. It shows substructured column density profiles and branches into two major filaments in the north. The masses in the filaments range between 130 and 1400 $M_\odot$, whereas the mass in the ridge is 15 000 $M_\odot$. The accretion of these filaments onto the DR21 ridge, suggested by a previous molecular line study, could provide a continuous mass inflow to the ridge. In contrast to the striations seen in, e.g., the Taurus region, these filaments are gravitationally unstable and form cores and protostars. These cores formed in the filaments potentially fall into the ridge. Both inflow and collisions of cores could be important to drive the observed high-mass star formation. The evolutionary gradient of star formation running from DR21 in the south to the northern branching is traced by decreasing dust temperature. This evolution and the ridge structure can be explained by two main filamentary components of the ridge that merged first in the south.

Key words. ISM: individual objects: DR 21 – ISM: general – ISM: structure – dust, extinction – stars: formation – ISM: individual objects: DR21(OH)

1. Introduction

The properties of dense structures in interstellar molecular clouds, e.g., the density and temperature distribution, chemical composition, and dynamics, are expected to determine the detailed outcome of the star formation process that varies between an isolated low-mass star and an OB star cluster. While previous observations have shown that clouds are filamentary (e.g., Bally et al. 1987), recent Herschel studies have revealed the ubiquity (e.g., Miville-Deschênes et al. 2010; Henning et al. 2010) and key importance of filaments for star formation. Notably, gravitationally unstable filaments are found to fragment into cores (André et al. 2010), and filaments generally show narrow central
widths of about 0.1 pc (Arzoumanian et al. 2011). Resulting self-gravitating cores with sizes of 0.01–0.1 pc and masses up to 10 $M_\odot$ are best candidates to form low- to possibly intermediate-mass stars (see reviews by Di Francesco et al. 2007; Ward-Thompson et al. 2007).

It is an important question which cloud structures lead to the formation of high-mass stars ($\geq 10 M_\odot$) that are almost exclusively found in stellar clusters or associations (see review by Zinnecker & Yorke 2007). The Herschel imaging survey of OB young stellar objects (HOBYS, Motte et al. 2010) observes massive molecular cloud complexes within 3 kpc distance to probe the cloud environment of OB star-forming cores, their statistical evolution, and the effects of feedback on parental clouds. Studying the Vela C region, Hill et al. (2011) suggested that “ridges”, i.e., massive, gravitationally unstable filamentary structures of high column density ($N_{H_2} > 10^{23}$ cm$^{-2}$) that dominate their environment could be preferential sites of high-mass star formation (cf. Nguyen Luong et al. 2011). The ridge in Vela C shows a complex substructure that could result from stellar feedback (Minier et al. 2012). Furthermore, intersecting filaments appear to mark sites of stellar cluster formation in the Rosette cloud (Schneider et al. 2012).

This study focuses on the DR21 ridge (also called DR21 filament), the densest and most massive cloud structure in the Cygnus X region (Schneider et al. 2006; Motte et al. 2007; Roy et al. 2011) at a distance of 1.4 kpc (Rygl et al. 2012). It hosts the embedded III region DR21 (e.g., Roelfsema et al. 1989), the maser source DR21(OH), and massive protostars (Bontemps et al. 2010). Schneider et al. (2010) analysed molecular line emission and identified three “sub-filaments” F1–F3 that connect to the ridge. Velocity gradients suggest that material is transported along them towards the ridge, and in the case of F3 a bend and possible direct connection to the DR21(OH) clump is traced (cf. Csengeri et al. 2011). This behaviour supports the scenario that sustained accretion of inflowing material plays a role in building up massive clumps and cores and that it sets the stage for high-mass star formation, as suggested by numerical simulations (e.g., Balsara et al. 2001; Banerjee et al. 2006; Smith et al. 2011). Here we exploit the unprecedented sensitivity of Herschel far-infrared and submillimeter continuum imaging to trace the detailed column density structure in this region.

2. Herschel observations and data reduction

Cygnus X North was observed in the parallel scan map mode with PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) on Dec. 18, 2010. To diminish scanning artefacts, two nearly perpendicular coverages of 2.8 x 2.8$^\circ$ were obtained in five photometric bands at 70, 160, 250, 350, and 500 $\mu$m with a scan speed of 20$''$/s. The data were reduced using the Herschel interactive processing environment and the Scanamorphos software (Roussel 2012, for creating PACS maps).

The 70 $\mu$m map traces in particular heated dust towards star-forming sites (Fig. 1a). To quantitatively estimate the distribution of the cold dust, which generally represents most of the dust mass, we created maps of column density $N_{H_2}$ and dust temperature $T_d$ in the way described in Hill et al. (2011, 2012), including offsets to recover the absolute intensity level following Bernard et al. (2010). Computed from the 160, 250, and 350 $\mu$m bands, the maps provide an angular resolution of 25$''$ (0.17 pc at 1.4 kpc). They have undefined values for pixel groups towards DR21, DR21(OH) (white pixels in Fig. 1b), and W75N (see Fig. B.1) due to saturation at 250 and 350 $\mu$m.

3. The DR21 filaments

We show in Fig. 1a compact 70 $\mu$m sources that are protostar candidates clustering along the DR21 ridge oriented north-south, with the most prominent peak being DR21 itself. Supposedly lying at the same distance, they show a strong northward decrease in luminosity. There are many filamentary streamers from the ridge to, e.g., the north-west and west, most of which were also detected in the mid-infrared with Spitzer (Marston et al. 2004;Hora et al. 2009). They mainly correspond to low column density structures (Fig. 1b), but several filaments are prominent. The extent of the DR21 ridge can be roughly defined by the $N_{H_2} = 10^{23}$ cm$^{-2}$ contour enclosing an area of 2.3 pc$^2$. Notably, the “sub-filaments” of Schneider et al. (2010), labelled F1 and F3, are recovered; both are resolved into nearly parallel northern and southern components that join close to the ridge. The northern part of the DR21 ridge shows two extensions in column density (“rabbit ears”) to the north and north-west (F1) that coincide with the coldest regions where the dust temperature drops as low as 14 K (Fig. 1c). The filaments are visible in the dust
temperature map as structures of lower central temperature relative to the background of ~19 K. The background column density level is \(10^{22} \text{ cm}^{-2}\) with a standard deviation of \(\sim 10^{21} \text{ cm}^{-2}\) mainly due to cirrus structure.

In the first step of characterising the DR21 filaments, we applied the DisPerSE software (Sousbie 2011) on the column density map to identify the filament crests, similar as Arzoumanian et al. (2011) and Hill et al. (2011), using a persistence threshold of \(3 \times 10^{21} \text{ cm}^{-2}\). Unlike for these works, possible line-of-sight confusion needed to be addressed in our analysis because of the low-density foreground cloud Cygnus Rift and the close-by W75N cloud component (e.g., Schneider et al. 2006). We also avoided the strong DR21 outflow (e.g., Richardson et al. 1986; White et al. 2010). Subsequent studies will analyse the combined column density, temperature, and kinematical data for a more extended region, but here we conservatively limited this study to filament segments that (1) have main velocities in \(^{13}\text{CO}\) coherent with the ridge and no strong secondary velocity components, and (2) have crest column densities above \(1.5 \times 10^{22} \text{ cm}^{-2}\); the resulting selection is shown in Fig. 1. At positions along their crests spaced by half the beam FWHM we extracted perpendicular column density profiles extending over 2.5 pc in each direction, wide enough for the outer profiles to be sufficiently flat and trace the background. For background column densities, we adopted the profile minima that were median-smoothed over 2.5 beam FWHM to lower the influence of neighbouring structures.

Crest column density and dust temperature are anti-correlated as anticipated for all filaments with the possible exception of SW (Fig. 2a, b). Contrary to the others, the latter shows slightly decreasing central temperature outward from the DR21 ridge. This filament also shows the weakest outward column density decline. In general, lower temperatures are expected for structures of higher column density because of the increased shielding from the interstellar radiation field. However, the SW filament is running towards the warmer area around DR21 (Fig. 1a, c) and possibly into the outflow cavity. Its inverted density-temperature relation could thus be an effect of heating by DR21.

The perpendicular filament column density profiles usually show a flattened central part and non-Gaussian, roughly power-law wings. To examine the central width we performed a weighted fit of a Gaussian curve plus a constant level (cf. Arzoumanian et al. 2011). As weights a Gaussian curve with 0.17 pc FWHM was used to ensure the reproduction of the central flattening. The central width of each profile was derived by building the cumulative integral over radial distance from the crest and determining the first minimum of its profile. This inverted density-temperature relation could thus be an effect of heating by DR21.

The perpendicular filament column density profiles usually show a flattened central part and non-Gaussian, roughly power-law wings. To examine the central width we performed a weighted fit of a Gaussian curve plus a constant level (cf. Arzoumanian et al. 2011). As weights a Gaussian curve with 0.17 pc FWHM was used to ensure the reproduction of the central flattening. The central width of each profile was derived by building the cumulative integral over radial distance from the crest and determining the first minimum of its profile.

### Table 1. Average properties of the DR21 filaments and ridge.

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>SW</th>
<th>F3S</th>
<th>F3N</th>
<th>F1S</th>
<th>F1N</th>
<th>N</th>
<th>Ridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (pc)</td>
<td>2.6</td>
<td>1.6</td>
<td>1.3</td>
<td>2.7</td>
<td>1.3</td>
<td>6.9</td>
<td>1.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Mean crest column density (a) (\times 10^{22} \text{ cm}^{-2})</td>
<td>4.4</td>
<td>1.2</td>
<td>1.6</td>
<td>2.1</td>
<td>7.7</td>
<td>1.9</td>
<td>4.8</td>
<td>41.6</td>
</tr>
<tr>
<td>Integration radius (pc)</td>
<td>0.58</td>
<td>0.41</td>
<td>0.24</td>
<td>0.24</td>
<td>0.48</td>
<td>0.39</td>
<td>0.49</td>
<td>1.15</td>
</tr>
<tr>
<td>Total mass ((M_\odot))</td>
<td>1350</td>
<td>210</td>
<td>130</td>
<td>400</td>
<td>960</td>
<td>1210</td>
<td>610</td>
<td>15210</td>
</tr>
<tr>
<td>Mean line mass ((M_\odot/\text{pc}))</td>
<td>500</td>
<td>120</td>
<td>100</td>
<td>140</td>
<td>700</td>
<td>170</td>
<td>520</td>
<td>3670</td>
</tr>
<tr>
<td>Weighted mean central width (b) (pc)</td>
<td>0.28 ± 0.07</td>
<td>0.31 ± 0.07</td>
<td>0.27 ± 0.08</td>
<td>0.32 ± 0.11</td>
<td>0.26 ± 0.07</td>
<td>0.33 ± 0.16</td>
<td>0.34 ± 0.17</td>
<td>0.34 ± 0.12</td>
</tr>
</tbody>
</table>

**Notes.**

\(a\) Background-subtracted column density. \(b\) The fit error in width \(\sigma_w\) was used for weighting data points with \(1/\sigma_w^2\).
that there the ridge consists of more than one individual filament. Considered together with the branching of the northern ridge into the “rabbit ears” (the F1 and N filaments) and the possible southern branching, this finding suggests that the DR21 ridge is a complex intersection of several individual filaments. The dominating filament along the crest shows a central width of ~0.34 pc, not significantly broader than the central widths of the filaments (Table 1).

5. Star formation in the DR21 ridge

Schneider et al. (2010) presented velocity gradients that suggest accretion of the filaments onto the DR21 ridge. Dust temperature dips are seen towards the filament-ridge connections (Fig. 2b), indicating that infalling material has cooled at these locations. At present, the total mass in the selected filaments is about 1/3 of the ridge mass. It thus appears that the mass assembly process of the DR21 ridge is in a late stage, possibly driven by the gravitational potential of the ridge itself, and specifically the build-up of massive cores in the DR21/DR21(OH) clumps could have been supported by continuous accretion from the S/SW and F3/S/F3N filaments, respectively. The filaments are for the most part gravitationally unstable and are forming cores and protostars. In contrast to the structures and “sub-filaments” in Taurus (Goldsmith et al. 2008; Palmeirim et al., in prep.) or Aquila (André et al. 2010). The high masses of the cores in the ridge could therefore not be generated by the merging processes involving a core merger process. High-mass star formation involving a core merger process was also suggested by observations of NGC 2264-C (Peretto et al. 2006).

The Herschel observations emphasize the evolutionary gradient along the ridge: beyond DR21, the 70 μm luminosity of protostars strongly decreases northward, and the dust temperature shows lowest temperatures towards the northern part. The substructure of the DR21 ridge suggests that it was formed by the merging of individual narrow, intersecting filaments. The pronounced elongation and branching into filaments F1 and N with the highest mass per unit length indicate that the major components may be roughly parallel filaments oriented north-south. At present, the merging could have advanced farthest in the southern part and less in the north, where the two components appear to be separated. Extrapolating this scenario, we expect that the northern filaments will lead to the assembly of one or more additional massive clumps. This study suggests that high-mass star-forming ridges could be second-generation cloud structures formed via dynamical merging of gravitationally unstable filaments.

Acknowledgements. SPIRE has been developed by a consortium of institutes led by Cardiff Univ. (UK) and including: Univ. Lethbridge (Canada); NAOC (China); CEA, LAM (France); IFSI, Univ. Padua (Italy); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCL-MSSL, UKATC, Univ. Sussex (UK); and Caltech, JPL, NHSC, Univ. Colorado (USA). This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, CNES, CNRS (France); ASI (Italy); MINE (Spain); SNSB (Sweden); STFC, UKSA (UK); and NASA (USA). PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KU Leuven, CSL, IMEC (Belgium); CEA, LAM (France); MPIA (Germany); INAF–IAPS/OAA/OAP/OAT, LENS, SISSA (Italy); IAC (Spain). This development has been supported by the funding agencies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNES (France), DLR (Germany), ASI/INAF (Italy), and CICYT/MCYT (Spain). This work was supported by the ANR (Agence Nationale pour la Recherche) project "PROBES" (ANR-08-BLAN-0241).
References

Appendix A: The S and F1N filaments in detail

Figure A.1 shows a zoom on the S and F1N filaments. Several compact, more or less elongated cores are seen in the 250 $\mu$m and column density map. The marked dense core N23 has an estimated mass of $13 M_\odot$.

Fig. A.1. Detailed view of filament S (panels a–c) and F1N (d–f). The 70 and 250 $\mu$m units are MJy/sr, column density unit is cm$^{-2}$. The black cross in panel a) indicates an extended 70 $\mu$m source. The blue ellipse in panels d–f) gives the position and extent (FWHM = semi-axes) of the dense core N23 of Motte et al. (2007).
Appendix B: Herschel maps of DR21 and Cygnus X North

Figure B.1 shows the DR21 environment in the Herschel maps of the HOBYS Cygnus X North observations together with a RGB colour-composite image.

**Fig. B.1.** Herschel maps of the DR21 environment in Cygnus X North obtained by HOBYS. Map units are MJy/sr. The last panel shows a RGB colour-composite image using the SPIRE 250 μm (red), PACS 160 μm (green), and PACS 70 μm (blue) maps.