$\text{H}_2\text{D}^+$: A LIGHT IN DARK PLACES, WHERE ALL OTHER LIGHTS FAIL

Cecilia Ceccarelli
Laboratoire d’Astrophysique de Grenoble, France
Introduction:

THE MATTER BUDGET IN THE UNIVERSE:

<table>
<thead>
<tr>
<th>DARK SETTOR</th>
<th>95.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>DARK ENERGY</td>
<td>72%</td>
</tr>
<tr>
<td>DARK MATTER</td>
<td>23%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BARYONIC MATTER</th>
<th>4.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>STARS</td>
<td>~4%</td>
</tr>
<tr>
<td>WARM/HOT INTERGALACTIC GAS</td>
<td>~50%?</td>
</tr>
<tr>
<td>? COLD GAS?</td>
<td>~50%?</td>
</tr>
</tbody>
</table>

A LARGE FRACTION OF BARYONIC MATTER IS STILL UNACCOUNTED FOR....
DARK MATTER in GALAXIES

FACTS:
✔ ROTATION CURVES --> MOST OF MATTER NOT IN OBSERVED COMPONENTS (stars, HI, H$_2$...)  
✔ “MISSING MATTER” NO DIFFUSE BARYONIC MATTER  
✔ BARYONIC CONDENSED FORM: BROWN DWARFS OR MACHOs RULED OUT BY OBS

A POSSIBLE EXPLANATION:
COLD (<10K), SMALL (<1000AU) AND DENSE (>10$^6$cm$^{-3}$) MOLECULAR CLOUDS: the CLOUDLETS
(Pfenninger et al. 1994; DePaolis et al. 1995; Gerhard & Silk 1996; Walker & Wardle 1998; Rafikov & Draine 2001; Kalberla et al. 1999; Ohishi et al. 2004...)

C.Ceccarelli, Rome Apr 2006
THE CLOUDLETS THEORY

NATURE AND ORIGIN OF CLOUDLETS: LARGELY DEBATED!

BASED ON SEVERAL ARGUMENTS (thermal stability, collisions, QSOs radio scintillations, micro-lensing obs...) (often using highly uncertain parameters, like the cosmic rays ionization rate at large gal distances...):

<table>
<thead>
<tr>
<th></th>
<th>&quot;Low&quot;</th>
<th>&quot;High&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ($M_\odot$)</td>
<td>0.001</td>
<td>1</td>
</tr>
<tr>
<td>Radius (AU)</td>
<td>10</td>
<td>1000</td>
</tr>
</tbody>
</table>

SOME EVIDENCES: high gal CO obs (Heithausen 2004), faint SCUBA sources (Lawrence 2001)...

C.Ceccarelli, Rome Apr 2006
WHY CLOUDLETS ARE “DARK” MATTER CANDIDATES

THE PROBE of GALACTIC COLD MOLECULAR GAS:
(dust continuum emission too weak to be detected)

A) CLOUDLETS FORMED BY ALMOST GALACTIC MATTER (but low in metals):
   -> CO FROZEN ONTO THE GRAINS
   (as all heavy-element bearing molecules)

B) CLOUDLETS FORMED BY PRIMORDIAL MATTER:
   -> NO CO AT ALL
   (as all heavy-element bearing molecules)

...HOW CAN SUCH A GAS BE PROBED???
FINDING A PROBE OF COLD H\(_2\) GAS

GAS PHASE MOLECULES FORMED BY H and D ATOMS:

i) neutral molecules

ii) ions created by the H\(_2\) ionization of cosmic rays

OBSERVABILITY:

/ no dipole or “high” energy ground transitions
FINDING A PROBE OF COLD H$_2$ GAS

FUNDAMENTAL TRANSITIONS:

372 GHz $\text{H}_2\text{D}^+$

692 GHz $\text{D}_2\text{H}^+$

OBSERVABLE WITH GROUND TELESCOPES
BUT ARE $\text{H}_2\text{D}^+$ and $\text{HD}_2^+$ ABUNDANT ENOUGH TO BE DETECTABLE ???

.... ELEMENTAL D/H $\sim 10^{-5}$

<table>
<thead>
<tr>
<th>STATISTICAL VALUES</th>
<th>IN SPECIAL CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim 10^{-5} \times (e^-)$</td>
<td>$\sim 0.1 \times (e^-)$</td>
</tr>
<tr>
<td>$\sim 10^{-10} \times (e^-)$</td>
<td>$\sim 0.1 \times (e^-)$</td>
</tr>
</tbody>
</table>

SPECIAL CONDITIONS = GAS COLD, DENSE AND DEVOITED OF HEAVY-ELEMENT BEARING MOLECULES... LIKE IN THE CLOUDLETS!
**H$_2$D$^+$ CHEMISTRY**

The chemistry in cold gas devoided of heavy-element bearing molecules is simple.

Cosmic rays + H$_2$ → ... → D$_3^+$$\rightarrow$HD$_2^+$$\rightarrow$H$_2$D$^+$$\rightarrow$H$_3^+$

For very low ionization degree, $x$(e$^-$) $\sim$ D$_3^+$$\rightarrow$HD$_2^+$$\rightarrow$H$_2$D$^+$$\rightarrow$H$_3^+$
$H_2D^+ & Co$ in CLOUDLETS:

Standard case:
$T=8K, \ n_{H_2}=10^7\text{cm}^{-3}, \ Z/Z_0=0.1, \ \zeta_{CR}=10^{-17}\text{s}^{-1}$

$x(H_2D^+) \sim 1/10 \ x(e^-)$
H$_2$D$^+$ OBSERVABILITY in CLOUDLETS

GUIDELINE EXAMPLE: NGC3198

$M_{\text{DARK HALO}} = 1.5 \times 10^{11} M_\text{O}$ ; $R_{\text{DARK HALO}} = 30\text{Kpc}$

“High” CASE:

$M_{\text{cloudlet}} = 1 M_\text{O}$, $R_{\text{cloudlet}} = 1000\text{AU}$  =>  $N(\text{H}_2\text{D}^+) = 10^{11} - 10^{13} \text{ cm}^{-2}$

“Low” CASE:

$M_{\text{cloudlet}} = 0.001 M_\text{O}$, $R_{\text{cloudlet}} = 10\text{AU}$  =>  $N(\text{H}_2\text{D}^+) = 10^{10} - 10^{12} \text{ cm}^{-2}$

$N(\text{H}_2\text{D}^+) = \tau < 1$ average column density in a 20” beam; depending on how the cloudlets are distributed in the halo, whether uniformly or centrally peaked.
H$_2$D$^+$ OBSERVATIONS in the GALAXY

PRE-STEellar CORES:
in the center T~8K and n~10$^6$cm$^{-3}$

PROTO-PLANETARY DISks
in the equatorial plane T<15K and n>10$^7$cm$^{-3}$

-> CO and heavy-elements bearing molecules are depleted like in the presumed cloudlets

H$_2$D$^+$ 372 GHz line observed in several objects: N(H$_2$D$^+$)~10$^{12}$cm$^{-3}$
(Caselli et al. 2003; Ceccarelli et al. 2004; van der Tak et al. 2005; Vastel et al. 2006...)

C.Ceccarelli, Rome Apr 2006
CONCLUSIONS: \( \text{H}_2\text{D}^+ \):

A LIGHT IN DARK PLACES, WHERE ALL OTHER LIGHTS FAIL

\( \text{H}_2\text{D}^+ \) SEEMS TO BE THE BEST TRACER WE HAVE SO FAR OF THE DARKEST REGION OF OUR GALAXY….

COLD DENSE GAS IS A CANDIDATE FOR DARK MATTER IN GALAXIES, SO FAR ONLY INDIRECTLY DETECTED BY ITS INFLUENCE ON GALACTIC ROTATION.

CAN \( \text{H}_2\text{D}^+ \) @ 372 GHZ BE THE LONG SOUGHT PROBE TO DETECT THIS GAS?


TO FRANCESCO WHO TAUGHT ME SO MUCH