The puzzle of protoplanetary disk masses

Miotello, A.

Citation

Miotello, A. (2018, March 7). *The puzzle of protoplanetary disk masses*. Retrieved from https://hdl.handle.net/1887/61006

Author: Miotello, A.
Title: The puzzle of protoplanetary disk masses
Issue Date: 2018-03-07

BIBLIOGRAPHY

Adams, F. C., Hollenbach, D., Laughlin, G., & Gorti, U. 2004, ApJ, 611, 360

Aikawa, Y., Miyama, S. M., Nakano, T., & Umebayashi, T. 1996, ApJ, 467, 684

Aikawa, Y., Umebayashi, T., Nakano, T., & Miyama, S. M. 1997, ApJL, 486, L51

Aikawa, Y., van Zadelhoff, G. J., van Dishoeck, E. F., & Herbst, E. 2002, A&A, 386, 622

Aikawa, Y., & Nomura, H. 2006, ApJ, 642, 1152

Akimkin, V., Zhukovska, S., Wiebe, D., et al. 2013, ApJ, 766, 8

Alcalá, J. M., Natta, A., Manara, C. F., et al. 2014, A&A, 561, A2

Alcalá, J. M., Manara, C. F., Natta, A., et al. 2017, A&A, 600, A20

Alexander, R., Pascucci, I., Andrews, S., Armitage, P., & Cieza, L. 2014, Protostars and Planets VI, 475

ALMA Partnership, Brogan, C. L., Pérez, L. M., et al. 2015, ApJL, 808, L3

Anderson, K. R., Adams, F. C., & Calvet, N. 2013, ApJ, 774, 9

André, P. 1995, Ap&SS, 224, 29

André, P., Men'shchikov, A., Bontemps, S., et al. 2010, A&A, 518, L102

Andrews, S. M., & Williams, J. P. 2005, ApJ, 631, 1134

Andrews, S. M., Wilner, D. J., Espaillat, C., et al. 2011, ApJ, 732, 42

Andrews, S. M., Wilner, D. J., Hughes, A. M., et al. 2012, ApJ, 744, 162

Andrews, S. M., Rosenfeld, K. A., Kraus, A. L., & Wilner, D. J. 2013, ApJ, 771, 129

Andrews, S. M. 2015, PASP, 127, 961

Andrews, S. M., Wilner, D. J., Zhu, Z., et al. 2016, ApJL, 820, L40

Ansdell, M., Williams, J. P., van der Marel, N., et al. 2016, arXiv:1604.05719

Ansdell, M., Williams, J. P., Manara, C. F., et al. 2017, AJ, 153, 240

Armitage, P. J. 2011, ARAA, 49, 195

Armitage, P. J., Simon, J. B., & Martin, R. G. 2013, ApJL, 778, L14

Armitage, P. J. 2015, arXiv:1509.06382

Astraatmadja, T. L., & Bailer-Jones, C. A. L. 2016, ApJ, 833, 119

Bai, X.-N., Ye, J., Goodman, J., & Yuan, F. 2016, ApJ, 818, 152

Bally, J., & Langer, W. D. 1982, ApJ, 255, 143

Barenfeld, S. A., Carpenter, J. M., Ricci, L., & Isella, A. 2016, arXiv:1605.05772

Bary, J. S., Weintraub, D. A., Shukla, S. J., Leisenring, J. M., & Kastner, J. H. 2008, ApJ, 678, 1088

Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Guesten, R. 1990, AJ, 99, 924

Bergin, E. A., Hogerheijde, M. R., Brinch, C., et al. 2010, A&A, 521, L33

Bergin, E. A., Cleeves, L. I., Gorti, U., et al. 2013, Nature, 493, 644

Bergin, E. A., Cleeves, L. I., Crockett, N., & Blake, G. 2014, arXiv:1405.7394

Bergin, E. A., Du, F., Cleeves, L. I., et al. 2016, ApJ, 831, 101

Birnstiel, T., Klahr, H., & Ercolano, B. 2012, A&A, 539, A148

Bisschop, S. E., Fraser, H. J., Öberg, K. I., van Dishoeck, E. F., & Schlemmer, S. 2006, A&A, 449, 1297

Bitner, M. A., Richter, M. J., Lacy, J. H., et al. 2008, ApJ, 688, 1326

Blake, G. A., van Dishoeck, E. F., & Sargent, A. I. 1992, ApJL, 391, L99

Boneberg, D. M., Panić, O., Haworth, T. J., Clarke, C. J., & Min, M. 2016, MNRAS, 461, 385

Brittain, S. D., Najita, J. R., & Carr, J. S. 2009, ApJ, 702, 85

Brown, J. M., Pontoppidan, K. M., van Dishoeck, E. F., et al. 2013, ApJ, 770, 94

Bruderer, S., van Dishoeck, E. F., Doty, S. D., & Herczeg, G. J. 2012, A&A, 541, A91

Bruderer, S. 2013, A&A, 559, A46

Bruderer, S., van der Marel, N., van Dishoeck, E. F., & van Kempen, T. A. 2014, A&A, 562, A26

Bustamante, I., Merín, B., Ribas, Á., et al. 2015, A&A, 578, A23

Cacciani, P., & Ubachs, W. 2004, Journal of Molecular Spectroscopy, 225, 62

Carmona, A., van den Ancker, M. E., Henning, T., et al. 2008, A&A, 477, 839

Carmona, A., van der Plas, G., van den Ancker, M. E., et al. 2011, A&A, 533, A39

Casassus, S., van der Plas, G., M, S. P., et al. 2013, Nature, 493, 191

Chiang, E. I., & Goldreich, P. 1997, ApJ, 490, 368

Chiang, E. I., Joung, M. K., Creech-Eakman, M. J., et al. 2001, ApJ, 547, 1077

Clarke, C. J., & Pringle, J. E. 1993, MNRAS, 261, 190

Clarke, C. J., Gendrin, A., & Sotomayor, M. 2001, MNRAS, 328, 485

Clarke, C. J. 2007, MNRAS, 376, 1350

Cleeves, L. I., Bergin, E. A., Alexander, C. M. O., et al. 2014, arXiv:1409.7398

Cleeves, L. I., Bergin, E. A., Qi, C., Adams, F. C., & Öberg, K. I. 2015, ApJ, 799, 204

Cleeves, L. I., Öberg, K. I., Wilner, D. J., et al. 2016, ApJ, 832, 110

Comerón, F. 2008, Handbook of Star Forming Regions, Volume II, 5, 295

Costigan, G., Vink, J. S., Scholz, A., Ray, T., & Testi, L. 2014, MNRAS, 440, 3444

D'Alessio, P., Calvet, N., & Hartmann, L. 2001, ApJ, 553, 321

D'Alessio, P., Calvet, N., Hartmann, L., Franco-Hernández, R., & Servín, H. 2006, ApJ, 638, 314

Dartois, E., Dutrey, A., & Guilloteau, S. 2003, A&A, 399, 773

de Gregorio-Monsalvo, I., Ménard, F., Dent, W., et al. 2013, A&A, 557, A133

Dent, W. R. F., Greaves, J. S., & Coulson, I. M. 2005, MNRAS, 359, 663

Dent, W. R. F., Thi, W. F., Kamp, I., et al. 2013, PASP, 125, 477

Draine, B. T. 1978, ApJS, 36, 595

Draine, B. T. 2006, ApJ, 636, 1114

Drozdovskaya, M. N., Walsh, C., Visser, R., Harsono, D., & van Dishoeck, E. F. 2015, MNRAS, 451, 3836

Du, F., Bergin, E. A., & Hogerheijde, M. R. 2015, ApJL, 807, L32

Du, F., Bergin, E. A., Hogerheijde, M., et al. 2017, ApJ, 842, 98

Dullemond, C. P., & Dominik, C. 2005, A&A, 434, 971

Dunham, M. M., Allen, L. E., Evans, N. J., II, et al. 2015, ApJS, 220, 11

Dutrey, A., Guilloteau, S., Duvert, G., et al. 1996, A&A, 309, 493

Dutrey, A., Guilloteau, S., & Guelin, M. 1997, A&A, 317, L55

Dutrey, A., Guilloteau, S., Prato, L., et al. 1998, A&A, 338, L63

Dutrey, A., di Folco, E., Guilloteau, S., et al. 2014, Nature, 514, 600

Eidelsberg, M., Benayoun, J. J., Viala, Y., et al. 1992, A&A, 265, 839

Eisner, J. A., Bally, J. M., Ginsburg, A., & Sheehan, P. D. 2016, ApJ, 826, 16

Eistrup, C., Walsh, C., & van Dishoeck, E. F. 2016, A&A, 595, A83

Evans, N. J., II, Dunham, M. M., Jørgensen, J. K., et al. 2009, ApJS, 181, 321-350

Facchini, S., Clarke, C. J., & Bisbas, T. G. 2016, MNRAS, 457, 3593

Facchini, S., Birnstiel, T., Bruderer, S., & van Dishoeck, E. F. 2017, A&A, 605, A16

Favre, C., Cleeves, L. I., Bergin, E. A., Qi, C., & Blake, G. A. 2013, ApJL, 776, L38

Fedele, D., van den Ancker, M. E., Henning, T., Jayawardhana, R., & Oliveira, J. M. 2010, A&A, 510, A72

Fedele, D., Bruderer, S., van Dishoeck, E. F., et al. 2013, ApJL, 776, L3

Fedele, D., Carney, M., Hogerheijde, M. R., et al. 2017, A&A, 600, A72

Field, G. B., Somerville, W. B., & Dressler, K. 1966, ARAA, 4, 207

Frerking, M. A., Langer, W. D., & Wilson, R. W. 1982, ApJ, 262, 590

Glover, S. C. O., & Jappsen, A.-K. 2007, ApJ, 666, 1

Goldsmith, P. F., Bergin, E. A., & Lis, D. C. 1997, ApJ, 491, 615

Gorti, U., & Hollenbach, D. 2004, ApJ, 613, 424

Gorti, U., & Hollenbach, D. 2009, ApJ, 690, 1539

Gorti, U., Hollenbach, D., Najita, J., & Pascucci, I. 2011, ApJ, 735, 90

Gorti, U., Liseau, R., Sándor, Z., & Clarke, C. 2016, Space Sci. Rew., 205, 125

Guilloteau, S., Dutrey, A., Piétu, V., & Boehler, Y. 2011, A&A, 529, A105

Hacar, A., & Tafalla, M. 2011, A&A, 533, A34

Hacar, A., Tafalla, M., Kauffmann, J., & Kovács, A. 2013, A&A, 554, A55

Haisch, K. E., Jr., Greene, T. P., Barsony, M., & Ressler, M. 2001, Bulletin of the American Astronomical Society, 33, 04.10

Harsono, D., Bruderer, S., & van Dishoeck, E. F. 2015, A&A, 582, A41

Hartmann, L., & Kenyon, S. J. 1985, ApJ, 299, 462

Hartmann, L., & Kenyon, S. J. 1987, ApJ, 312, 243

Hartmann, L., Calvet, N., Gullbring, E., & D'Alessio, P. 1998, ApJ, 495, 385

Hartmann, L. 2000, Accretion processes in star formation, Vol. 32 (CambridgeUniversity Press)

Hartmann, L., Herczeg, G., & Calvet, N. 2016, ARAA, 54, 135

Hayashi, C. 1981, Fundamental Problems in the Theory of Stellar Evolution, 93, 113

Helled, R., Bodenheimer, P., Podolak, M., et al. 2014, Protostars and Planets VI, 643

Herbst, E., & van Dishoeck, E. F. 2009, ARAA, 47, 427

Hernández, J., Calvet, N., Briceño, C., et al. 2007, ApJ, 671, 1784

Herczeg, G. J., & Hillenbrand, L. A. 2008, ApJ, 681, 594-625

Hildebrand, R. H. 1983, QJRAS, 24, 267

Hogerheijde, M. R., Bergin, E. A., Brinch, C., et al. 2011, Science, 334, 338

Hollenbach, D., Gorti, U., Meyer, M., et al. 2005, ApJ, 631, 1180

Howat, S. K. R., Timmermann, R., Geballe, T. R., Bertoldi, F., & Mountain, C. M. 2002, ApJ, 566, 905

Hudson, R. D. 1971, Reviews of Geophysics and Space Physics, 9, 305

Isella, A., Guidi, G., Testi, L., et al. 2016, Physical Review Letters, 117, 251101

Izidoro, A., Morbidelli, A., Raymond, S. N., Hersant, F., & Pierens, A. 2015, A&A, 582, A99

Johnstone, D., Hollenbach, D., & Bally, J. 1998, ApJ, 499, 758

Jones, M. G., Pringle, J. E., & Alexander, R. D. 2012, MNRAS, 419, 925

Jonkheid, B., Faas, F. G. A., van Zadelhoff, G.-J., & van Dishoeck, E. F. 2004, A&A, 428, 511

Kama, M., Bruderer, S., Carney, M., et al. 2016, A&A, 588, A108

Kama, M., Bruderer, S., van Dishoeck, E. F., et al. 2016, A&A, 592, A83

Kamp, I., Tilling, I., Woitke, P., Thi, W.-F., & Hogerheijde, M. 2010, A&A, 510, A18

Kamp, I., Woitke, P., Pinte, C., et al. 2011, A&A, 532, A85

Kastner, J. H., Qi, C., Gorti, U., et al. 2015, ApJ, 806, 75

Kelly, B. C. 2007, ApJ, 665, 1489

Kennicutt, R. C., & Evans, N. J. 2012, ARAA, 50, 531

Kenyon, S. J., & Hartmann, L. 1987, ApJ, 323, 714

Kóspál, Á., Moór, A., Juhász, A., et al. 2013, ApJ, 776, 77

Lacy, J. H., Knacke, R., Geballe, T. R., & Tokunaga, A. T. 1994, ApJL, 428, L69

Lada, C. J. 1987, Star Forming Regions, 115, 1

Langer, W. D., Graedel, T. E., Frerking, M. A., & Armentrout, P. B. 1984, ApJ, 277, 581

Letzelter, C., Eidelsberg, M., Rostas, F., Breton, J., & Thieblemont, B. 1987, Chemical Physics, 114, 273

Levison, H. F., Kretke, K. A., & Duncan, M. J. 2015, Nature, 524, 322

Lissauer, J. J., Hubickyj, O., D'Angelo, G., & Bodenheimer, P. 2009, Icarus, 199, 338

Lommen, D., Maddison, S. T., Wright, C. M., et al. 2009, A&A, 495, 869

Lynden-Bell, D., & Pringle, J. E. 1974, MNRAS, 168, 603

Lyons, J. R., & Young, E. D. 2005, Chondrites and the Protoplanetary Disk, 341, 193

Manara, C. F., Fedele, D., Herczeg, G. J., & Teixeira, P. S. 2016, A&A, 585, A136

Manara, C. F., Rosotti, G., Testi, L., et al. 2016, A&A, 591, L3

Mannings, V., & Sargent, A. I. 1997, ApJ, 490, 792

Matsuo, T., Shibai, H., Ootsubo, T., & Tamura, M. 2007, ApJ, 662, 1282

McClure, M. K., Bergin, E. A., Cleeves, L. I., et al. 2016, ApJ, 831, 167

Meeus, G., Salyk, C., Bruderer, S., et al. 2013, A&A, 559, A84

Merín, B., Brown, J. M., Oliveira, I., et al. 2010, ApJ, 718, 1200-1223

Miotello, A., Testi, L., Lodato, G., et al. 2014, A&A, 567, A32

Miotello, A., Bruderer, S., & van Dishoeck, E. F. 2014, A&A, 572, AA96

Miotello, A., van Dishoeck, E. F., Kama, M., & Bruderer, S. 2016, A&A, 594, A85

Miotello, A., van Dishoeck, E. F., Williams, J. P., et al. 2017, A&A, 599, A113

Morbidelli, A., & Raymond, S. N. 2016, Journal of Geophysical Research (Planets), 121, 1962

Mohanty, S., Jayawardhana, R., & Basri, G. 2005, ApJ, 626, 498

Müller, H. S. P., Schlöder, F., Stutzki, J., & Winnewisser, G. 2005, Journal of Molecular Structure, 742, 215

Najita, J., Carr, J. S., & Mathieu, R. D. 2003, ApJ, 589, 931

Nakagawa, T., Shibai, H., Onaka, T., et al. 2014, in SPIE Astronomical Telescopes+ Instrumentation, International Society for Optics and Photonics, 9143, 91431I

Natta, A., Testi, L., Neri, R., Shepherd, D. S., & Wilner, D. J. 2004, A&A, 416, 179

Nomura, H., Aikawa, Y., Nakagawa, Y., & Millar, T. J. 2009, A&A, 495, 183

Öberg, K. I., Murray-Clay, R., & Bergin, E. A. 2011, ApJL, 743, L16

O'dell, C. R., & Wen, Z. 1994, ApJ, 436, 194

Ossenkopf, V., & Henning, T. 1994, A&A, 291, 943

Owen, J. E., Ercolano, B., Clarke, C. J., & Alexander, R. D. 2010, MNRAS, 401, 1415

Panić, O., Hogerheijde, M. R., Wilner, D., & Qi, C. 2008, A&A, 491, 219

Panić, O., & Hogerheijde, M. R. 2009, A&A, 508, 707

Pascucci, I., Gorti, U., Hollenbach, D., et al. 2006, ApJ, 651, 1177

Pascucci, I., Herczeg, G., Carr, J. S., & Bruderer, S. 2013, ApJ, 779, 178

Pascucci, I., Testi, L., Herczeg, G. J., et al. 2016, ApJ, 831, 125

Pérez, L. M., Carpenter, J. M., Chandler, C. J., et al. 2012, ApJL, 760, L17

Perez, S., Casassus, S., Ménard, F., et al. 2015, ApJ, 798, 85

Pfalzner, S., Vogel, P., Scharwächter, J., & Olczak, C. 2005, A&A, 437, 967

Pinilla, P., Birnstiel, T., Ricci, L., et al. 2012, A&A, 538, A114

Pollack, J. B., Hollenbach, D., Beckwith, S., et al. 1994, ApJ, 421, 615

Pollack, J. B., Hubickyj, O., Bodenheimer, P., et al. 1996, Icarus, 124, 62

Pontoppidan, K. M., Blake, G. A., van Dishoeck, E. F., et al. 2008, ApJ, 684, 1323

Prodanović, T., Steigman, G., & Fields, B. D. 2010, MNRAS, 406, 1108

Regály, Z., Juhász, A., Sándor, Z., & Dullemond, C. P. 2012, MNRAS, 419, 1701

Ricci, L., Testi, L., Natta, A., et al. 2010, A&A, 512, A15

Roberts, H., & Millar, T. J. 2000, A&A, 364, 780

Rodmann, J., Henning, T., Chandler, C. J., Mundy, L. G., & Wilner, D. J. 2006, A&A, 446, 211

Roelfsema, P., Giard, M., Najarro, F., et al. 2014, Proc. SPIE, 9143, 91431K

Röllig, M., & Ossenkopf, V. 2013, A&A, 550, A56

Romero, G. A., Schreiber, M. R., Cieza, L. A., et al. 2012, ApJ, 749, 79

Ros, K., & Johansen, A. 2013, A&A, 552, A137

Rosenfeld, K. A., Andrews, S. M., Hughes, A. M., Wilner, D. J., & Qi, C. 2013, ApJ, 774, 16

Rosotti, G. P., Clarke, C. J., Manara, C. F., & Facchini, S. 2017, MNRAS, 468, 1631

Sargent, A. I., & Beckwith, S. 1987, ApJ, 323, 294

Schoonenberg, D., & Ormel, C. W. 2017, A&A, 602, A21

Schwarz, K. R., Bergin, E. A., Cleeves, L. I., et al. 2016, ApJ, 823, 91

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337

Shirley, Y. L., Huard, T. L., Pontoppidan, K. M., et al. 2011, ApJ, 728, 143

Smith, D., & Adams, N. G. 1980, ApJ, 242, 424

Smith, B. A., & Terrile, R. J. 1984, Science, 226, 1421

Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451

Suzuki, T. K., Ogihara, M., Morbidelli, A., Crida, A., & Guillot, T. 2016, A&A, 596, A74

Tazzari, M., Testi, L., Ercolano, B., et al. 2016, A&A, 588, A53

Tazzari, M., Testi, L., Natta, A., et al. 2017, arXiv:1707.01499

Testi, L., Natta, A., Shepherd, D. S., & Wilner, D. J. 2003, A&A, 403, 323

Testi, L., Birnstiel, T., Ricci, L., et al. 2014, Protostars and Planets VI, astro-ph/1402.1354

Thi, W. F., Blake, G. A., van Dishoeck, E. F., et al. 2001, Nature, 409, 60

Thommes, E. W., Matsumura, S., & Rasio, F. A. 2008, Science, 321, 814

Trapman, L., Miotello, A., Kama, M., van Dishoeck, E. F., & Bruderer, S. 2017, arXiv:1705.07671

Turner, N. J., Fromang, S., Gammie, C., et al. 2014, Protostars and Planets VI, 411

van Dishoeck, E. F., & Black, J. H. 1988, ApJ, 334, 771

van Dishoeck, E. F., Jonkheid, B., & van Hemert, M. C. 2006, Faraday Discussions, 133, 231

van der Marel, N., van Dishoeck, E. F., Bruderer, S., et al. 2013, Science, 340, 1199

van der Marel, N., van Dishoeck, E. F., Bruderer, S., Pérez, L., & Isella, A. 2015, A&A, 579, A106

van der Marel, N., van Dishoeck, E. F., Bruderer, S., et al. 2016, A&A, 585, A58

van der Plas, G., van den Ancker, M. E., Acke, B., et al. 2009, A&A, 500, 1137

van Leeuwen, F. 2007, A&A, 474, 653

van Zadelhoff, G.-J., van Dishoeck, E. F., Thi, W.-F., & Blake, G. A. 2001, A&A, 377, 566

Varnière, P., & Tagger, M. 2006, A&A, 446, L13

Viala, Y. P., Letzelter, C., Eidelsberg, M., & Rostas, F. 1988, A&A, 193, 265

Visser, R., van Dishoeck, E. F., & Black, J. H. 2009, A&A, 503, 323

Walmsley, C. M., Flower, D. R., & Pineau des Forêts, G. 2004, A&A, 418, 1035

Walsh, K. J., Morbidelli, A., Raymond, S. N., O'Brien, D. P., & Mandell, A. M. 2011, Nature, 475, 206

Walsh, C., Juhász, A., Pinilla, P., et al. 2014, ApJL, 791, L6

Walsh, C., Nomura, H., & van Dishoeck, E. 2015, A&A, 582, A88

Watson, W. D., Anicich, V. G., & Huntress, W. T., Jr. 1976, ApJL, 205, L165

Weidenschilling, S. J. 1977, MNRAS, 180, 57

Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296

Whipple, F. L. 1972, From Plasma to Planet, 211

Willacy, K., & Woods, P. M. 2009, ApJ, 703, 479

Williams, J. P., Andrews, S. M., & Wilner, D. J. 2005, ApJ, 634, 495

Williams, J. P., & Cieza, L. A. 2011, ARAA, 49, 67

Williams, J. P., & Best, W. M. J. 2014, ApJ, 788, 59

Williams, J. P., & McPartland, C. 2016, ApJ, 830, 32

Wilson, T. L., & Rood, R. 1994, ARAA, 32, 191

Woitke, P., Kamp, I., & Thi, W.-F. 2009, A&A, 501, 383

Woitke, P., Pinte, C., Tilling, I., et al. 2010, MNRAS, 405, L26

Woitke, P., Min, M., Pinte, C., et al. 2016, A&A, 586, A103

Wolcott-Green, J., & Haiman, Z. 2011, MNRAS, 412, 2603

Woodall, J., Agúndez, M., Markwick-Kemper, A. J., & Millar, T. J. 2007, A&A, 466, 1197

Woods, P. M., & Willacy, K. 2009, ApJ, 693, 1360

Wright, C. M., van Dishoeck, E. F., Cox, P., Sidher, S. D., & Kessler, M. F. 1999, ApJL, 515, L29

Wynn-Williams, C. G. 1982, ARAA, 20, 587

Yu, M., Willacy, K., Dodson-Robinson, S. E., Turner, N. J., & Evans, N. J., II 2016, ApJ, 822, 53

Zhang, X., Liu, B., Lin, D. N. C., & Li, H. 2014, ApJ, 797, 20

Zhang, K., Bergin, E. A., Blake, G. A., Cleeves, L. I., & Schwarz, K. R. 2017, Nature Astronomy, 1, 0130

Zhu, Z., Nelson, R. P., Hartmann, L., Espaillat, C., & Calvet, N. 2011, ApJ, 729, 47

SAMENVATTING

De kosmos zit in ons.
We zijn gemaakt van sterrenstof.
We zijn een manier voor het heelal om zichzelf te kennen.
Carl Sagan

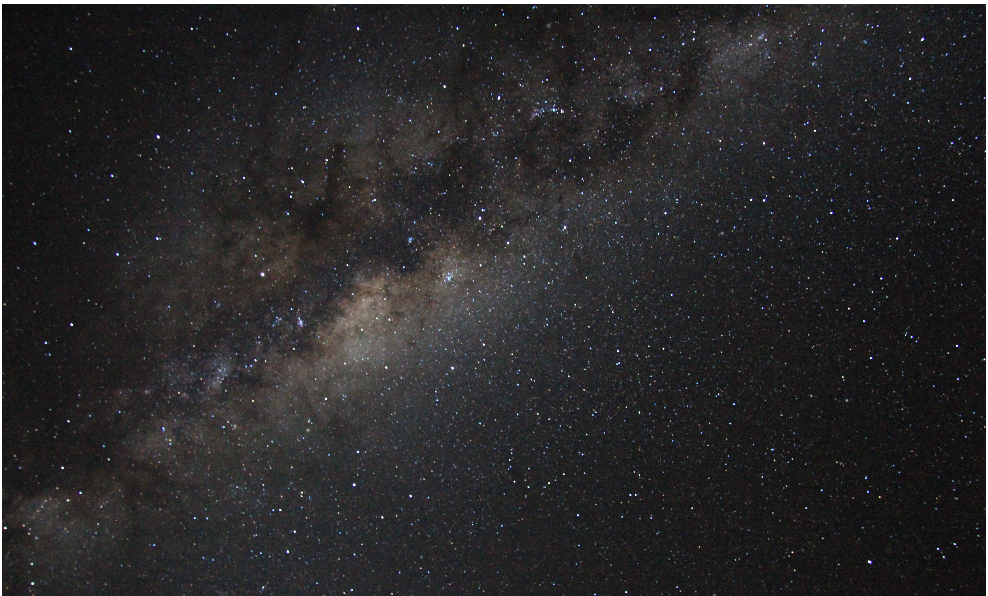


Figure 7.1: Foto van het galactisch centrum en de Melkweg – vol met donkere stofwolken – vanaf Cerro Paranal tijdens nieuwe maan op 26 maart 2017 (foto genomen door de auteur met een spiegelreflexcamera, belichting 30 sec).

Sinds het begin van de mensheid heeft men omhoog gekeken naar de nachtelijke hemel en zich verwonderd over de betekenis van zo'n majestieuze voorstelling (Fig. 7.1). Oude beschavingen over de hele wereld, van Egypte tot China en van Oceanië tot Zuid-Amerika, kenden mythen en legendes over de sterrenbeelden en nevelachtige objecten die ze aan de hemel zagen. Ook gedurende onze Europese geschiedenis zijn vele dichters, schilders en kunstenaars geïnspireerd geweest door hemelse verschijnselen. De verbazing over de nachtelijke hemel is altijd hand in hand gegaan met het verlangen om de relatie tussen mensheid en universum te begrijpen. Zelfs nu de wetenschap en technologie verder ontwikkeld zijn, en we de fysische en chemische structuur van astronomische objecten kunnen verklaren, blijft deze vraag ons bezig houden. De wetenschap heeft onthuld dat de verbinding tussen de cosmos en ons bestaan veel inniger is dan de wildste pre-wetenschappelijke voorstellingen. Onze kennis over het sterrenstelsel waarin wij ons bevinden vertelt ons bijvoorbeeld dat alle verschijnselen in de Melkweg, van zwarte gaten en ontploffende supernovae tot de exacte locatie van ons zonnestelsel, hebben samengewerkt om te zorgen dat leven kon evolueren tot hoe wij dat nu kennen. Daarnaast kunnen we door de groeiende populatie van ontdekte exoplaneten hun eigenschappen vergelijken met die van ons eigen planetenstelsel. Ondanks het grote aantal bekende planetenstelsels lijkt de inrichting van ons eigen zonnestelsel erg “speciaal” te zijn. Uit omvangrijke studies naar exoplaneten blijkt dat een zon-Jupiter systeem maar in één op duizend planetenstelsels wordt waargenomen. Maar aan de andere kant voorspellen theoretische modellen dat Jupiter een fundamentele rol heeft gespeeld in de evolutie van ons zonnestelsel.

Vorming van sterren en protoplanetaire schijven

De vraag over onze oorsprong is gecentreerd rond de vorming van sterren en planeten. Hoe vormen sterren en de planeten die om hen heen draaien? Wat zijn de beginvoorwaarden om een planetenstelsel zoals het onze te vormen? Welke rol speelt de fysische structuur en de chemische samenstelling van deze stelsels in wording?

De vorming van sterren begint op grote schaal met het ontstaan van filamenten in gigantische moleculaire wolken. Waarnemingen hebben laten zien dat deze filamenten langgerekte structuren zijn waarin zich in het algemeen tientallen kleinere draadvorminge structuren vormen. Deze draden vallen uiteindelijk uiteen in kernen met zeer hoge dichtheden die we *pre-stellaire kernen* noemen, omdat ze waarschijnlijk instorten om één of meerdere sterren te vormen. Tijdens dit ineenstorten wordt er een draaiende schijfvormige structuur gevormd zodat het hoekmoment behouden blijft. Via deze schijf beweegt materiaal naar binnen om uiteindelijk in de groeiende protoster te vallen (Fig. 7.2). We noemen het een *protoplanetaire schijf* omdat het de plaats is waar planeten, zoals de aarde en de andere planeten in ons zonnestelsel,

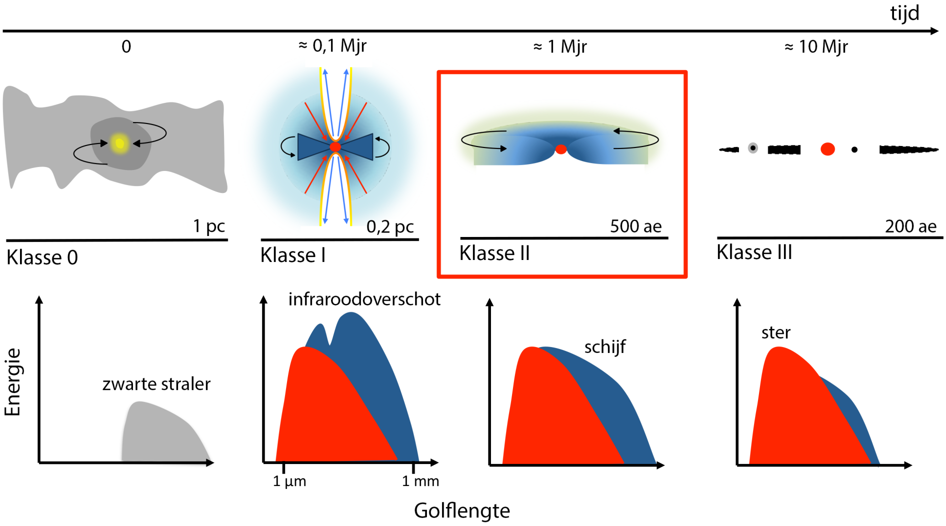


Figure 7.2: Illustratie van de vorming van een ster en daaromheen draaiende planeten. De verschillende evolutionaire stadia zijn weergegeven in de bovenste rij. De onderste rij laat de bijbehorende waarneembare kenmerken zien in de vorm van schematische Spectrale Energie Diagrammen (SEDs). Dit proefschrift richt zich op het Klasse II stadium.

gevormd worden.

Protoplanetaire schijven evolueren van een beginstadium waarin ze nog omhuld worden door een grote hoeveelheid gas en stof (Klasse 0 en Klasse I objecten) naar een meer typerende fase waarin ze veel gas herbergen en het omhulsel verdwenen is (Klasse II). In het volgende stadium bevatten ze nog maar weinig gas en moeten grotere lichamen zoals planeten en asteroiden al gevormd zijn (Klasse III). Zoals te zien in de illustratie in Fig. 7.2 worden de diverse evolutionaire stadia gekenmerkt door verschillen in de vorm van hun Spectrale Energie Diagram (SED). Dit proefschrift richt zich op het modeleren van het gas in protoplanetaire schijven tijdens de gasrijke Klasse II fase en het vergelijken van deze resultaten met spiksplinternieuwe waarnemingen van gas en stof in schijven gedaan met de Atacama Large Millimeter/submillimeter Array (ALMA, zie Fig. 7.3).

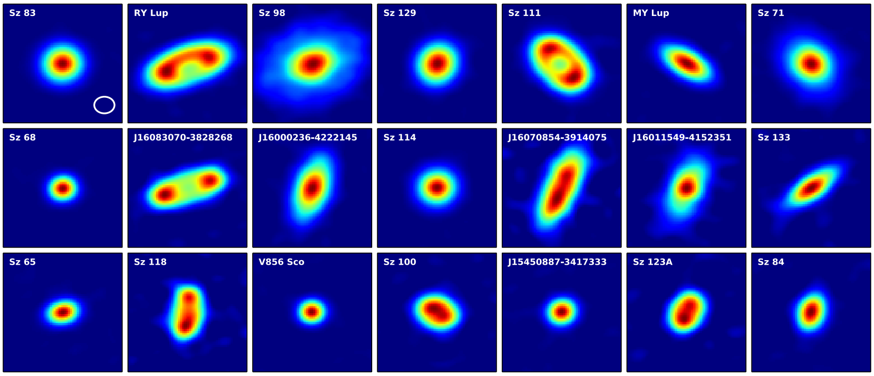


Figure 7.3: Compositie van protoplanetaire schijven die met ALMA zijn waargenomen in het stervormingsgebied Lupus en die illustratief zijn voor de grote variëteit aan type schijven. De afbeeldingen laten de thermische straling zien bij een golflengte van 890 μm. Deze straling wordt uitgezonden door stofdeeltjes in de schijf die een grootte hebben van enkele millimeters. Figuur door M. Ansdell.

Openstaande vragen omtrent protoplanetaire schijven

De totale massa is een fundamentele eigenschap van een schijf, want het bepaalt niet alleen zijn structuur en evolutie, maar ook de kenmerken van het planetenstelsel dat uiteindelijk gevormd wordt. Desondanks is het nog niet gelukt om de massa's van schijven met grote zekerheid af te leiden uit waarnemingen. Schijven bestaan uit gas en stof, en hoewel het gas 99% van de massa uitmaakt, is het het stof dat grotendeels bepaalt wat voor straling uitgezonden wordt. Daar komt nog bij dat het merendeel van het stof bestaat uit deeltjes van enkele millimeters die niet noodzakelijkerwijs goed gemengd zijn met het gas. Om deze redenen zou de massa van het gas en stof dus apart gemeten moeten worden. Verwacht wordt dat het grootste gedeelte van de schijfmassa bestaat uit moleculair waterstof (H_2). H_2 is echter moeilijk waar te nemen, omdat het niet gemakkelijk geëxciteerd wordt bij de lage temperaturen die heersen in het merendeel van de schijf. Van oudsher wordt daarom de aanwezigheid van gas in schijven afgeleid aan de hand van koolstofmonoxide (CO) emissielijnen die wel gemakkelijk geëxciteerd worden. Maar omdat deze emissie in het algemeen optisch dik is is het erg moeilijk, en modelafhankelijk, om met behulp van CO de gasmassa nauwkeurig te bepalen. De belangrijkste vragen die in dit proefschrift behandeld worden zijn de volgende:

- Wat kan het best gebruikt worden als maatstaaf voor de gasmassa in protoplanetaire schijven? Zijn de minder voorkomende isotopologen[1] van CO hiervoor

---

[1] Isotopologen zijn moleculen die enkel van elkaar verschillen in hun isotoop samenstelling. Simpel

geschikt? Kan gedeutereerd waterstofgas (HD) een goed alternatief zijn en wat zijn hiervan de beperkingen?

- Hoe kunnen huidige en toekomstige waarnemingen met ALMA[2] gebruikt worden om de massa's te bepalen van een statistisch significant aantal schijven?
- Wat is de daadwerkelijke verhouding tussen de gas- en stofmassa in schijven, en hoe wordt de bepaling hiervan beïnvloed door het feit dat een deel van de koolstof en zuurstof opgesloten kan zitten in rotsachtig materiaal?

Dit proefschrift en een toekomstperspectief

Het bepalen van gasmassa's in schijven is vanaf het begin de rode draad geweest door dit proefschrift. CO isotopologen zijn al vele jaren veelbelovende kandidaten voor het meten van de gasmassa, en door de opkomst van ALMA kunnen zij routinematig waargenomen worden in schijven. Openstaande vragen zijn of chemische isotoop-specifieke processen een belangrijke rol spelen in de verhouding waarin de verschillende isotopologen van CO voorkomen en bij het bepalen van de gasmassa. Het minder voorkomende isotopoloog $C^{18}O$ wordt inderdaad sneller afgebroken door uv-straling dan de hoofdvorm van koolstofmonoxide, $^{12}C^{16}O$. Dit proefschrift begint daarom vanuit een modeleerperspectief. Inmiddels heeft de *Lupus Disk Survey*, uitgevoerd met ALMA, het aantal waarnemingen van CO isotopologen in schijven sterk vergroot, en de modellen die gepresenteerd worden in Hoofdstuk 3 zijn hiermee vergeleken. Hiernaast zijn nog een aantal op (toekomstige) waarnemingen gerichte onderzoeken gedaan.

- Hoofdstuk 2 beschrijft voor het eerst de correcte behandeling van isotoop-specifieke fotolyse in een fysisch-chemisch model voor schijven, genaamd DALI. Isotoop-specifieke fotolyse is het proces dat de onderlinge verhoudingen van de CO isotopologen in de laag waar de CO emissie vandaan komt het meest beïnvloedt. In dit model worden de ^{13}CO, $C^{18}O$ en $C^{17}O$ isotopologen behandeld als aparte soorten in een chemisch netwerk. Daarnaast worden de chemie, de temperatuur structuur, en het stralingstransport van zowel lijn- als continuümstraling in beschouwing genomen. Het belangrijkste resultaat is dat in bepaalde gebieden in de schijf isotoop-specifieke processen leiden tot verhoudingen van de isotopologen die afwijken van de isotoopverhoudingen van

---

gezegd heeft een isotopoloog tenminste één atoom met een ander aantal neutronen dan het normale molecuul.

[2] ALMA is een internationaal samenwerkingsverband tussen de European Southern Observatory (ESO), de Amerikaanse National Science Foundation (NSF) en de National Institutes of Natural Sciences (NINS) van Japen, samen met NRC (Canada), NSC en ASIAA (Taiwan), en KASI (Korea), en in samenwerking met Chili.

de elementen. Dit betekent dat schijfmassa's onderschat kunnen worden met meer dan een orde van grootte als de verhouding tussen de isotopologen als constant wordt beschouwd.

- In Hoofdstuk 3 wordt de kleine set modellen die in Hoofdstuk 2 gebruikt zijn om de effecten van isotoop-specifieke CO fotolyse te onderzoeken, uitgebreid. Meer dan 800 schijfmodellen zijn gedraaid voor een reeks verschillende parameters voor de ster en schijf. Voor verschillende inclinaties is de totale fluxdichtheid berekend voor lage *J* overgangen van verschillende CO isotopologen. Dit hoofdstuk laat zien dat de totale schijfmassa afgeleid kan worden uit een combinatie van de totale intensiteit van ^{13}CO en C^{18}O, maar met een grotere foutmarge dan uit voorgaande onderzoeken is gebleken. Deze onnauwkeurigheid kan verkleind worden als de grootte van de schijf, de inclinatie en de kromming van het schijfoppervlak bekend zijn uit andere waarnemingen. De totale intensiteit van de lijnemissie van een aantal lage *J* overgangen van verschillende CO isotopologen wordt gepresenteerd en beschreven met eenvoudige vergelijkingen. Verder zijn de effecten van een verminderde hoeveelheid koolstof in het gas en van verschillende verhoudingen tussen de hoeveelheid gas en stof onderzocht.

- In Hoofdstuk 4 worden de fysisch-chemische modellen uit Hoofdstuk 3 gebruikt om waarnemingen van stof en CO isotopologen (^{13}CO $J = 3-2$ en C^{18}O $J = 3-2$) in schijven in Lupus te analyzeren. Uit eerdere studies stond het aantal schijven waarvoor de gasmassa berekend was op tien. Dit aantal is aanzienlijk vergroot door voor 34 objecten de gasmassa te bepalen. Dit hoofdstuk laat zien dat, als aangenomen wordt dat de hoeveelheid vluchtig koolstof niet verlaagd is, de gasmassa's gebaseerd op CO in het algemeen erg laag zijn voor schijven rond sterren met een zonsachtige massa: vaak minder dan 1 $M_{\rm Jup}$ (massa van Jupiter). Als gevolg hiervan is de globale verhouding tussen de hoeveelheid gas en stof veel lager dan de verwachte waarde van 100 (de waarde in het interstellaire medium). Voor de meeste schijven ligt deze waarde tussen 1 en 10. Lage waardes voor de op CO gebaseerde gasmassa en de verhouding tussen gas en stof kan wijzen op een snel verlies van gas. Andere mogelijke oorzaken zijn chemische evolutie, bijvoorbeeld de omzetting van CO in meer complexe moleculen, of de opslag van koolstof in grotere objecten. De eerste hypothese betekent dat de vorming van reuzenplaneten snel moet gaan of zeldzaam is. Voor de andere verklaring is de betekenis voor de tijdschaal waarop planeetvorming plaatsvindt minder duidelijk.

- In Hoofdstuk 5 wordt met de DALI modellen een andere belangrijke schijfeigenschap onderzocht, namelijk de verdeling van de oppervlaktedichtheid van het gas ($\Sigma_{\rm gas}$). Robuuste metingen van $\Sigma_{\rm gas}$ aan de hand van waarnemingen is essentieel om de evolutie van schijven, en het onderlinge belang daarbij van verschillende processen, te begrijpen, alsmede hoe planeten gevormd worden. Recentelijk zijn heeft ALMA waarnemingen gemaakt van de intensiteit van ^{13}CO emissie als functie van de afstand tot de ster. Dit hoofdstuk onderzoekt of zulke metingen gebruikt kunnen worden als maat voor de oppervlaktedichtheid van het gas over de lengte van de schijf. Uit vergelijkingen met de DALI modellen vinden we dat de intensiteitsverdeling van ^{13}CO alleen vergelijkbaar is met de oppervlaktedichtheidsverdeling van het gas in het middelste gedeelte van de schijf. In het binnenste gedeelte dicht bij de ster is de emissie optisch dik en neemt daardoor (relatief) af. In de buitenste gebieden neemt de emissie af door een combinatie van vastvriezen aan stofdeeltjes en inefficiënte zelfbescherming tegen uv-straling.

- In Hoofdstuk 6 is een simpele deuterium chemie toegevoegd aan het chemische netwerk in DALI om HD lijnemissie te simuleren. Het doel is om te onderzoeken hoe robuust deze emissie is als maat voor de gasmassa in schijven, en dan met name wat het effect is van de gasmassa op de ver-infraroodstraling van HD, en hoe gevoelig deze emissie is voor de vertikale structuur van de schijf. De onzekerheid in de op HD gebaseerde massabepaling blijkt schappelijk te zijn, en waarnemingen van HD moeten beschouwd worden als een belangrijk wetenschappelijk doel voor toekomstige ver-infrarood-missies zoals SPICA.

De voornaamste conclusies van dit proefschrift zijn als volgt.

1. Isotoop-specifieke fotolyse van CO moet op de juiste wijze in beschouwing genomen worden bij het modeleren van emissie van zeldzame CO isotopologen. Als dit niet gebeurt kan de lijnemissie van C^{18}O overschat worden, en de hiervan afgeleide gasmassa onderschat met een orde van grootte, of zelfs meer.

2. De gasmassa van een schijf kan bepaald worden aan de hand van een combinatie van de totale ^{13}CO en C^{18}O intensiteit, alhoewel de foutmarge hierbij niet verwaarloosbaar is: voor de meest zware schijven kan dit wel twee orden van grootte bedragen.

3. Gasmassa's gebaseerd op CO zijn extreem laag voor schijven in Lupus: vaak minder dan 1 $M_{\rm Jup}$. De globale verhouding tussen de gas- en stofmassa ligt voornamelijk tussen 1 en 10. Dit zou geïnterpreteerd kunnen worden als een snel verlies van gas. Het alternatief is een snelle chemische evolutie waarbij CO is omgezet in andere moleculen en dus geen goede maat meer is voor de totale gasmassa.

4. Waarnemingen van ^{13}CO met een hoekoplossend vermogen groter dan de afmetingen van de schijf kunnen de vorm van de schijf's oppervlaktedichtheidsverdeling afbakenen, mits optische diepte, bevriezing en zelfbescherming tegen uv-straling op de juiste manier behandeld worden in de modellen.

5. Straling van HD in het ver-infrarood kan gebruikt worden om de gasmassa van schijven te bepalen. De foutmarge is hierbij schappelijk en wordt met name veroorzaakt door de vertikale structuur in de schijf. Dergelijke waarnemingen moeten beschouwd worden als een belangrijk wetenschappelijk doel voor toekomstige ver-infraroodmissies.

Het blijft een openstaande vraag hoeveel de gasmassa in schijven bedraagt. CO isotopologen zijn nog steeds veelbelovende kandidaten voor het bepalen van de massa, omdat ze routinematig met ALMA kunnen worden waargenomen. Maar deze methode moet wel geijkt worden. Dit proefschrift laat zien dat isotoop-specifieke fotolyse belangrijk is voor een goede massabepaling aan de hand van CO isotopologen. Fotolyse is echter niet de voornaamste reden voor zwakke lijnemissie van CO isotopologen, in ieder geval niet voor de TW Hya schijf, maar mogelijk ook in andere schijven. Een proces dat verder onderzocht en beter begrepen moet worden is de afname van vluchtig koolstof. Waar belandt dit koolstof? Het waarnemen van iets complexere moleculen zoals de koolwaterstoffen C_2H en c-C_3H_2 zou een manier kunnen zijn om de op CO gebaseerde gasmassa's te ijken. Een andere optie is waarnemingen van [CI], omdat hieruit de hoeveelheid vluchtig koolstof in de bovenste lagen van een schijf kan worden afgeleid. Als uiteindelijk HD emissielijnen met voldoende spectrale resolutie waargenomen kunnen worden met SPICA, dan hebben we een onafhankelijke maat voor de gasmassa in schijven.

Het bepalen van de totale massa van protoplanetaire schijven is niet gemakkelijk. Toch is dit cruciaal omdat het de belangrijkste schijfeigenschap is die nodig is om het ontstaan te begrijpen van planeten zoals onze eigen aarde en de grote verscheidenheid aan exoplaneten[3].

---

[3] Exoplaneten zijn planeten die om een andere ster dan de zon draaien.

SUMMARY

The cosmos is within us.
We are made of star-stuff.
We are a way for the universe to know itself.
Carl Sagan

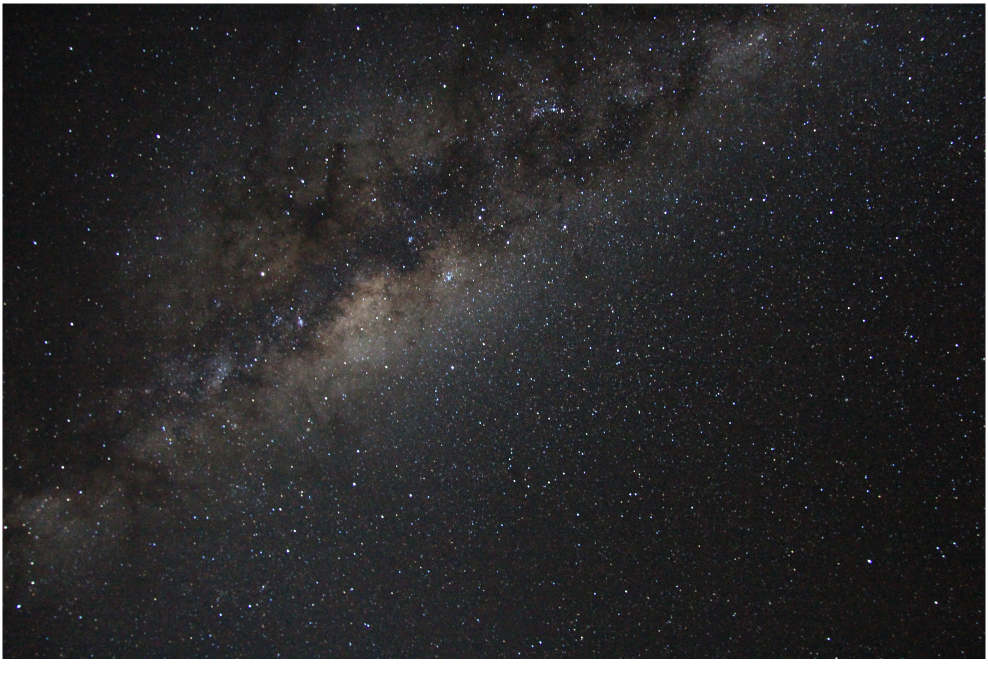


Figure 8.1: The galactic center and dusty Milky Way as seen on March 26, 2017 on a new moon night from Cerro Paranal (photo taken by the author with Reflex camera, exposure 30s).

Since the beginning of human history, men have raised their eyes to the night sky and wondered about the meaning of such a majestic show (Fig. 8.1). Ancient civilizations from different parts of the world, from Egypt to China, from Oceania to southern America, have given life to myths and legends about the constellations and nebulosities that they could spot in the sky. Even throughout our European history many poets, painters and artists have taken inspiration from celestial events. The astonishment in front of the sky has always been accompanied by the need to understand the link between mankind and the universe. Now that science and technology have advanced and we are able to explain the physical and chemical structure of astronomical objects, this question has not been abandoned. Science has revealed to us that the connection of the cosmos with our existence is much deeper than any pre-scientific vision had dared to imagine. For example our knowledge on our hosting galaxy tells us that all phenomena happening in the Milky Way, from the presence of a black hole to that of supernova explosions up to the actual location of our Solar System, have cooperated to allow life to evolve up to the current status. Also, the growing zoo of discovered exoplanets allows us to compare their characteristics with those of our planetary system. Despite the large statistics, it seems that the configuration of our own Solar System is very "special". Based on exoplanet observational surveys, the Sun-Jupiter system is as common as one in a thousand. On the other hand theoretical modeling favors Jupiter as the fundamental player in the Solar System's evolution.

Star formation and protoplanetary disks

The question about our origins centers around star and planet formation. How do stars and planets orbiting around them form? What are the initial conditions needed to generate a planetary system similar to our own? Which roles do the physical architecture and chemical composition of these forming systems play?

On large scales, star formation begins with the formation of filamentary structures inside giant molecular clouds. Observations have shown that filaments are elongated structures, within which typically several dozens of smaller fibers are created and eventually fragment into dense cores. These are defined as *prestellar cores*, as they will likely collapse to form one or more stars. As the collapse proceeds, due to conservation of angular momentum a rotating disk-like structure is formed, through which matter accretes onto the forming protostar (Fig. 8.2). This is called *protoplanetary disk* as it is also the place where planets, like our own Earth and the other Solar System planets, are formed.

Disks evolve from an initial phase where they are still embedded in their extended envelope (Class 0 and Class I objects), to a more typical stage in which they are gas-rich and the envelope has been dissipated (Class II objects), to a more evolved

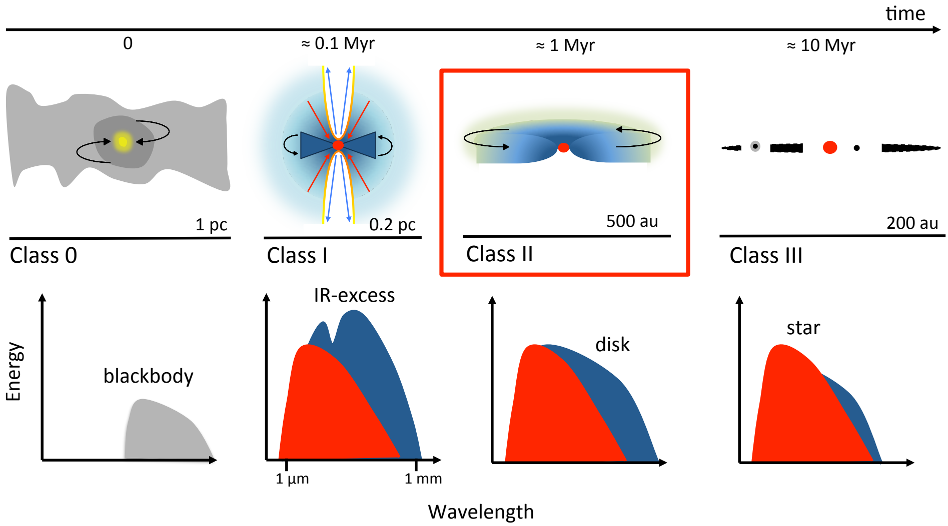


Figure 8.2: Sketch of the star and planet formation process in isolation. In the upper panel different evolutionary classes are sketched, while in the lower panel the respective observational features are shown through schematic SEDs. This thesis focuses on the stage of a pre-main sequence star with a disk, called the Class II stage.

phase where they are gas-poor and larger bodies, such as planets and asteroids, must be already formed (Class III objects). As shown by the sketch in Fig. 8.2, the different evolutionary stages have different slopes in their Spectral Energy Distributions (SED). The focus of this thesis is on protoplanetary disks in their gas rich Class II phase through the modeling of their bulk gas component and comparing with brand-new observations of images of gas and dust in disks from the Atacama Large Millimeter/submillimeter Array (ALMA, see Fig. 8.3).

Open questions in the study of protoplanetary disks

One of the fundamental properties of disks is the total *mass*, as it determines their physics, evolution and the characteristics of the planetary outcomes. Nevertheless disk masses are not yet observationally determined with high confidence. Disks are composed of gas, accounting for 99% of the mass, and dust, which in turn dominates the emission. The bulk of the dust mass is in mm-sized grains, which are not necessarily well mixed with the gas. Accordingly the mass determination of the gaseous and dusty components should in principle be carried out independently. Most of

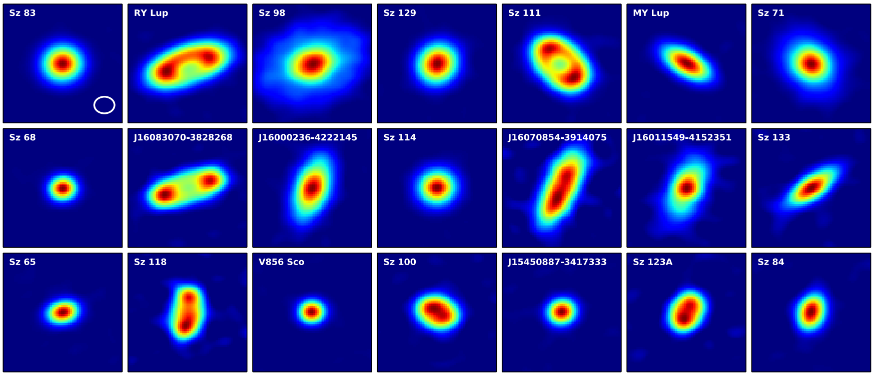


Figure 8.3: Image showing the zoo of protoplanetary disks observed with ALMA in the Lupus Star Forming region. These images show the dust thermal emission at 890 μm caused by mm-sized grains present in the disks (Credit: M. Ansdell).

the disk mass is expected to be in the form of molecular gas, essentially molecular hydrogen (H_2). However, H_2 is not easily excited and observable at the cold temperatures in the bulk of the disk. Hence, traditionally, the presence of gas in disks has been constrained through carbon monoxide (CO) emission lines, easily excited in disks. However the emission is generally very optically thick, so using CO to measure accurately the gas mass is very difficult and model dependent. The main questions that are tackled in this PhD thesis are the following.

- Which is the best gas mass tracer in protoplanetary disks? Could the less abundant isotopologues[1] of CO serve this purpose? Would hydrogen deuteride (HD) be a good alternative and what are its limitations?

- How can current and future ALMA observation be used to determine the masses of a statistically significant sample of disks?

- What is the actual gas-to-dust mass ratio in disks and how is its determination affected by the fact that a fraction of the carbon and oxygen may be locked up in refractory material?

---

[1] Isotopologues are molecules that differ only in their isotopic composition. Simply, the isotopologue of a chemical species has at least one atom with a different number of neutrons than the parent.

This thesis and future outlook

Determining disk gas masses has been the leading question of this PhD thesis since its origin. CO isotopologues have been promising gas mass tracer candidates for many years and with the advent of ALMA their detection in disks has become routine. The still open question is if chemical isotope-selective effects play a major role in setting the mutual abundance ratios of CO isotopologues and in the determination of disk masses. The rarer isotopologue $C^{18}O$ is indeed destroyed by UV radiation faster than the main form of carbon monoxide, $^{12}C^{16}O$. Therefore this thesis starts from the modeling perspective. Subsequently a larger sample of CO isotopologues observations in disks has been provided by the *Lupus Disk Survey* with ALMA . The grid of models presented in Chapter 3 has therefore been compared with observations and some more observation-motivated projects have been carried out.

- In Chapter 2 isotope-selective photodissociation, the main process controlling the relative abundances of CO isotopologues in the CO-emissive layer, was properly treated for the first time in a physical-chemical disk model called DALI. The chemistry, thermal balance, line, and continuum radiative transfer were all considered together with a chemical network that treats ^{13}CO, $C^{18}O$ and $C^{17}O$, isotopologues as independent species. The main result is that isotope selective processes lead to regions in the disk where the isotopologues abundance ratios are considerably different from the elemental ratios. Accordingly, considering CO isotopologue ratios as constants may lead to underestimating disk masses by up to an order of magnitude or more.

- In Chapter 3 the small grid of models used in Chapter 2 to investigate the effects of CO isotope-selective photodissociation has been expanded. More than 800 disk models have been run for a range of disk and stellar parameters. Total fluxes have been ray-traced for different CO isotopologues and for various low $J-$ transitions for different inclinations. This chapter shows that a combination of ^{13}CO and $C^{18}O$ total intensities allows inference of the total disk mass, although with larger uncertainties, compared with the earlier studies. These uncertainties can be reduced if one knows the disk's radial extent, inclination and flaring from other observations. Finally, total line intensities for different CO isotopologue and for various low-J transitions are provided as functions of disk mass and fitted to simple formulae. The effects of a lower gas-phase carbon abundance and different gas-to-dust ratios are investigated as well.

- In Chapter 4 the grid of physical-chemical models presented in Chapter 3 has been employed to analyze continuum and CO isotopologues (^{13}CO $J = 3-2$ and $C^{18}O$ $J = 3-2$) observations of Lupus disks. Disk gas masses have been calculated for a total of 34 sources, expanding the sample of 10 disks studied previously. This chapter shows that overall CO-based gas masses are very low for disks orbiting a solar mass-like star, often smaller than $1M_{\rm J}$ (mass of Jupiter), if volatile carbon is not depleted. Accordingly, global gas-to-dust ratios are much lower than the expected ISM-value of 100, being predominantly between 1 and 10. Low CO-based gas masses and gas-to-dust ratios may indicate rapid loss of gas, or alternatively chemical evolution, e.g. via sequestering of carbon from CO to more complex molecules, or carbon locked up in larger bodies. The first hypothesis would imply that giant planet formation must be quick or rare, while for the latter the implication on planet formation timescales is less obvious.

- In Chapter 5 another important disk property has been investigated with DALI models, i.e. the gas surface density distribution $\Sigma_{\rm gas}$. Reliable observational measurements of $\Sigma_{\rm gas}$ are key to understand disk evolution and the relative importance of different processes, as well as how planet formation occurs. This chapter investigates whether ^{13}CO line radial profiles, such as those recently acquired by ALMA, can be employed as a probe of the gas surface density profile. By comparing with DALI simulations we find that ^{13}CO radial profiles follow the density profile in the middle-outer disk. The emission drops in the very inner disk due to optical depth, and in the very outer disk due to a combination of freeze-out and inefficient self-shielding.
- In Chapter 6 simple deuterium chemistry has been added to the chemical network in DALI to simulate HD lines in disks. The aim is to examine the robustness of HD as a tracer of the disk gas mass, specifically the effect of gas mass on the HD far infrared emission and its sensitivity to the disk vertical structure. The uncertainty on HD-mass determination due to disk structure is found to be moderate and HD observations should be considered as an important science goal for future far-infrared missions, such as SPICA.

The main conclusions of this thesis are the following:

1. CO isotope-selective photodissociation needs to be properly considered when modeling rare CO isotopologues emission. Otherwise, C^{18}O lines emission could be overestimated and the derived gas masses could be underestimated by up to an order of magnitude or more.
2. Disk gas masses can be inferred by a combination of ^{13}CO and C^{18}O total intensities, although with non-negligible uncertainties, up to two orders of magnitude for very massive disks.
3. CO-based disk gas masses derived in Lupus are extremely low, often smaller than 1 $M_{\rm J}$ and the global gas-to-dust ratios are predominantly between 1 and

10. This may be interpreted as either rapid loss of gas, or fast chemical evolution.

4. The shape of the disk surface density distribution can be constrained by spatially resolved ^{13}CO observations, if optical depth, freeze-out and self shielding are properly considered in the modeling.

5. HD far-infrared emission can be used to determine disk gas masses with moderate uncertainty which depends mainly on the disk vertical structure. Such observations should be considered as an important science goal for future far-infrared missions.

The question on disk gas masses remains open. CO isotopologues are still promising mass tracers candidates, as their detection is routine for ALMA, but they need to be calibrated. This thesis shows that the process of isotope-selective photodissociation is important for a good interpretation of CO isotopologues as gas mass tracers. However photodissociation, at least for the case of TW Hya and possibly for other disks, is not the main process responsible for the observed faint CO isotopologues lines. In turn, volatile carbon depletion is a process that needs to be further investigated and understood. Where does the carbon go? The detection of slightly more complex molecules, such as the hydrocarbons C_2H and c-C_3H_2 could be a way to calibrate CO-based gas masses. Another option is to enlarge the sample of [CI] line detections, which allow inference of the volatile carbon abundance in the upper regions of the disk. Finally, if the HD fundamental lines can be covered at high enough spectral resolution with SPICA, their detection will provide an unique independent tracer of the disk mass.

Determining the total mass of protoplanetary disks is challenging but crucial, as this is the main disk property that one needs in order to understand how planets such as our own Earth or the diverse observed exo-planets[2] form.

---

[2] Exo-planets are planets orbiting a star that is not the Sun.

RIASSUNTO

> *Il cosmo é dentro di noi.*
> *Siamo fatti di materia stellare.*
> *Noi siamo il modo in cui l'universo puó conoscere se stesso.*
> Carl Sagan

Figure 9.1: Fotografia del centro galattico e della Via Lattea ottenuta il 26 Marzo 2017 in una notte di luna nuova a Cerro Paranal in Cile (la fotografia é stata scattata dall'autrice con una macchina fotografica Reflex ed un'esposizione di 30 secondi).

Fin dall'inizio della storia dell'umanitá, gli uomini hanno alzato gli occhi al cielo stellato e si sono interrogati sul significato di quello stupendo spettacolo (vedi Figura 9.1). Le piú antiche civilizzazioni in varie parti del mondo, dall'Egitto alla Cina, dall'Oceania all'America del Sud, hanno dato vita a miti e leggende legati alle costellazioni e alle nebulositá che riuscivano ad identificare nel cielo. Anche in Europa, in varie epoche storiche, poeti, pittori e artisti si sono ispirati agli eventi celesti. Lo stupore davanti al cielo stellato é stato sempre accompagnato dal desiderio di comprendere il legame tra l'umanitá e l'universo. Questa domanda non ci ha abbandonato, anche ora che la scienza e la tecnologia si sono svilutppate e siamo in grado di spiegare la struttura chimica e fisica di molti oggetti astronomici. La scienza ci ha rivelato che la connessione tra il cosmo e la nostra esistenza é ancora piú profonda di quanto si potesse immaginare in una visione pre-scientifica. Ad esempio, la conoscienza della nostra galassia ci ha permesso di scoprire che tutti i fenomeni che accadono nella Via Lattea, dalla presenza di un buco nero alle esplosioni di supernova fino alla paticolare localizzazione del nostro Sistema Solare, hanno cooperato a permettere che la vita si sviluppasse sulla Terra fino allo stato attuale. Inoltre, lo zoo - sempre in crescita - di pianeti scoperti recentemente attorno ad altre stelle ci ha permesso di paragonare le caratteristiche di questi "exo-pianeti" con quelle del nostro sistema planetario. Nonostante la statistica elevata, sembra che la configurazione del Sistema Solare sia "speciale". Basandosi sulle osservazioni di exo-pianeti, la combinazione di una stella come il Sole e di un pianeta come Giove ha la probabilitá di accadere una volta su un milione. I modelli teorici ci dicono invece che Giove é stato probabilmente un elemento chiave per lo sviluppo del nostro Sistema Solare.

Formazione stellare e dischi protoplanetari

La domanda ancora aperta riguardo la nostra origine é strettamente legata alla formazione stellare e planetaria. Come nascono le stelle ed i pianeti che orbitano attorno ad esse? Quali sono le condizioni iniziali necessarie per generare un sistema planetario simile al nostro? Che ruolo giocano la morfologia e la composizione chimica nella formazione ed evoluzione di questi sistemi?

A grandi scale la formazione stellare inizia con la creazione di strutture filamentari all'interno di giganti nubi molecolari. Le osservazioni hanno mostrato che i filamenti sono strutture elongate all'interno delle quali si possono trovare parecchie dozzine di fibre piú piccole che infine collasseranno sotto l'effetto della propria gravitá e si frammenteranno in nuclei densi. Questi ultimi vengono chiamati *nuclei prestellari*, dato che il loro collasso porterá alla formazione di una o piú stelle. Mentre il collasso procede, per la conservazione del momento angolare, una struttura rotante a forma di disco viene generata e permette l'accrescimento di materiale sulla protostella in formazione (Figura 9.2). Questa struttura é chiamata *disco protoplan-*

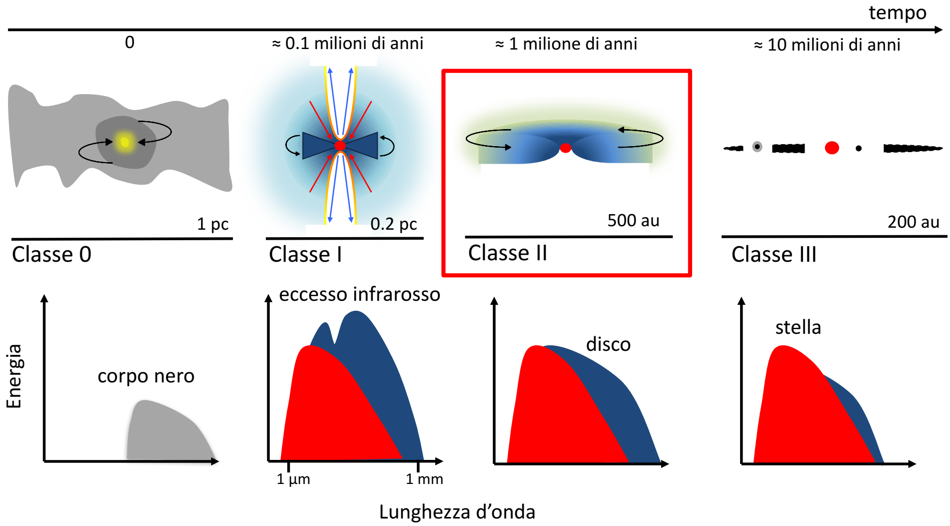


Figure 9.2: Rappresentazione schematica della formazione stellare e planetaria in un contesto isolato. Nel pannello superiore vengono presentate le varie classi evolutive, mentre nel pannello sottostante vengono mostrate le caratteristiche osservative legate ad ad ogni fase attraverso una semplificazione della SED (Distribuzione di Energia Spettrale). Questa tesi si concentra sulla fase di una stella di pre-sequenze principale circondata da un disco, chiamata Classe II.

etario dato che rappresenta anche il luogo dove i pianeti - come la Terra e gli altri elementi del Sistema Solare - vengono generati.

I dischi evolvono da una fase iniziale nella quale sono ancora immersi nel loro inviluppo (oggetti di Classe 0 e Classe I), ad uno stadio tipico nel quale essi sono ricchi di gas ed il loro inviluppo é stato dissipato (oggetti di Classe II), fino ad una fase piú evoluta dove essi sono poveri di gas ed al loro interno oggetti estesi, come pianeti ed asteroidi, devono giá essersi formati (oggetti di Classe III). Come mostrato dallo schema in Figura 9.2, da un punto di vista osservativo la forma della Distribuzione Spettrale di Energia (SED) puó darci informazioni sulla fase evolutiva degli oggetti osservati. Questa tesi si focalizza sullo studio dei dischi protoplanetari di Classe II, quindi ricchi di gas, attraverso la modelizzazione della loro componente gassosa ed attraverso il paragone con nuove immagini di gas e polvere in dischi ottenute con l' Atacama Large Millimeter/submillimeter Array (ALMA[1], vedi Figura 9.3).

---

[1] ALMA é un partenariato internazionale dello European Southern Observatory (ESO), della Fon-

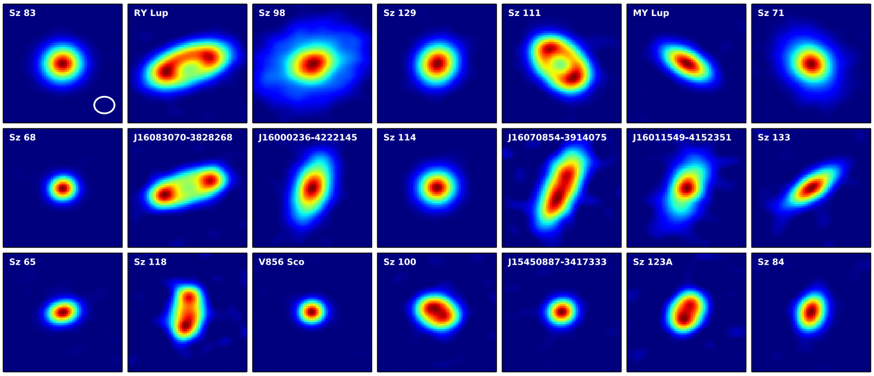


Figure 9.3: "Zoo" dei dischi protoplanetari osservati con ALMA nella regione di formazione stellare in Lupo. Queste immagini mostrano l'emissione temica della polvere a 890 μm causata dalla presenza si grani millimetrici nei dischi (Credit: M. Ansdell).

Domande aperte nello studio dei dischi protoplanetari

Una delle proprietá fondamentali dei dischi é la loro *massa* totale, dato che essa determina la loro evoluzione e le caratteristiche dei pianeti si che andranno a formare. Nonstante ció, le masse dei dischi non sono ancora state determinate accuratamente tramite osservazioni. I dischi sono composti per il 99 % della loro massa da gas, e da polvere - per il restante 1% della massa - che peró domina l'emissione osservabile. La maggior parte della massa di polvere risiede in grani della dimensione del millimetro, che non necessariamente sono ben mescolati con il gas. Proprio per questo la determinazione della massa del gas e della polvere dovrebbe essere fatta indipendentemente. Ci si aspetta che la maggior parte della massa del disco sia nella forma di gas molecolare, in particolare di idrogeno molecolare (H_2). Tuttavia le righe dell' H_2 non sono facilmente eccitate e quindi osservabili alle basse temperature a cui si trova la maggior parte del materiale nei dischi. Di conseguenza, tradizionalmente la presenza di gas nei dischi é stata rilevata tramitele righe di emissione del monossido di carbonio (CO), che invece vengono eccitate facilmente alle condizioni termo-fisiche trovate nei dischi. Tuttavia l'emissione di queste righe é generalmente otticamente spessa, quindi é difficile sfruttarla per determinare le masse dei dischi in maniera accurata e dipende dai modellu utilizzati. Le principali domande affrontate da questa tesi di dottorato sono le seguenti:

---

dazione Nazionale Scientifican negli U.S.A. (NSF) e dell' Istituto Nazionale di Scienze Naturali (NINS) del Giappone, insieme al NRC (Canada), NSC e ASIAA (Taiwan), e KASI (Repubblica di Korea), in cooperazione con la Repubblica del Cile.

- Qual'é il miglior tracciante della massa dei dischi protoplanetari? Possono gli isotopologi [2] meno abbondanti del CO essere una soluzione? É possibile che il deuteruro di idrogeno (HD) sia una buona alternativa e quali sono le sue limitazioni?
- Come possono osservazioni - presenti e future - ottenute con ALMA essere usate per determinare la massa di un numero statisticamente interessante di dischi?
- Qual'é la vera frazione di massa in gas e polvere nei dischi e come la sua determinazione é contaminata dal fatto che parte del carbonio e dell'ossigeno possano essere bolccati in materiale refrattario?

Questa tesi e le sue prospettive future

Determinare la massa di gas nei dischi protoplanetari é stata la domanda che ha guidato questa tesi di dottorato fin dalla sua nascita. Gli isotopologi del CO sono stati considerati come promettenti traccianti della massa per molti anni e con l'avvento di ALMA il loro rilevamento é diventato routine.

La domanda ancora aperta é se effetti chimici, che agiscono selettivamente su diversi Isotopologi, giochino un ruolo importante nel regolare le abbondanze relative tra i diversi isotopologi del CO e nella determinazione della massa dei dischi. L'isotopologo piú raro, il $C^{18}O$, é infatti distrutto dalla radiazione UV piú velocemente del classico monossido di carbonio, il $^{12}C^{16}O$. Questa tesi inizia quindi la sua investigazione da un punto di vista teorico. Successivamente un insieme di osservazioni degli isotopologi del CO in dischi sono state rese disponibili dalla *Survey di Dischi in Lupus* con ALMA. La griglia di modelli presentati nel Capitolo 3 sono quindi stati paragonati con le osservazioni e alcuni progetti motivati dai dati osservati sono stati realizzati.

- Nel Capitolo 2 la fotodissociazione selettiva degli isotopologi, ovvero il processo che principlamente controlla le abbondanze relative degli isotopologi del CO nella zona del disco dove esso emette, é stata trattata in modo accurato per la prima volta in un modello fisico-chimico di dischi chiamato DALI. La chimica, il bilancio termico ed il trasporto radiativo del continuo e delle righe sono stati considerati contemporaneamente con un network chimco che tratta ^{13}CO, $C^{18}O$ e $C^{17}O$ come speci indipendenti. Il risultato principale é che processi chimici selettivi degli Isotopologi portano ad avere regioni del disco dove la

---

[2] Gli isotopologi sono molecole che hanno come unica differenza la loro composizione isotopica. Semplicemente, l'isotopologo di una specie chimica ha almeno un atomo con un numero di neutroni differente dalla molecola madre.

frazione delle abbondanze di diversi isotopologi é molto diversa dalla frazione isotopica degli elementi. Di conseguenza, assumere queste frazioni con i valori costanti ottenuti dalle frazioni isotopiche puó portare a sottostimare le masse dei dischi di piú di un ordine di grandezza.

- Nel capitolo 3 la piccola griglia di modelli usata nel Capitolo 2 é stata espansa. Piú di 800 modelli sono stati lanciati per coprire un spettro di parametri stellari e del disco molto piú ampio. I flussi integrati delle righe di emissione sono stati simulati per diversi isotopologi del CO nelle basse transizioni rotazionali e per varie inclinazioni del disco. Questo capitolo mostra che combinando i flussi totali di riga del ^{13}CO e del C^{18}O é possibile ricavare la massa totale dei dischi, anche se con incertezze non trascurabili in paragone a studi precedenti. Queste incertezze possono essere ridotte se l'estensione radiale e verticale e l' inclinazione del disco sono note da dati osservativi. Infine, le intensitá di linea totali per diversi isotopologi del CO e per varie transizioni rotazionali sono fornite e fittate con semplici relazioni analitiche. Sono stati anche investigati gli effeti provocati sia dalla bassa abbondanza di carbonio nello stato gassoso, che di basse frazioni di massa di gas su massa di polvere.

- Nel capitolo 4 la griglia di modelli presentati nel capitolo 3 é stata utilizzata per analizzare il continuo e le righe degli isotopologi del CO (^{13}CO $J = 3-2$ e C^{18}O $J = 3-2$) osservati nel dischi in Lupus. Le masse del gas dei dischi sono state calcolate per 34 sorgenti, espandendo il gruppo di 10 dischi studiati precedentemente. Questo capitolo mostra che in generale le masse di gas basate sul CO sono estremamente basse per dischi che orbitano stelle di tipo solare, spesso piú basse di una massa di Giove se l'abbondanza di carbonio non é ridotta. Di conseguenza, le frazioni di massa di gas-su-polvere sono molto piú basse del valore aspettato 100 che é osservato nel mezzo interstellare, oscillando princioalmente tra 1 e 10. Masse del gas e frazioni di massa di gas-su-polvere basate sul CO cosí basse possono indicare una perdita di gas molto rapida, o, alternativamente, un' evoluzione chimica che sequestrerebbe il carbonio dal CO per bloccarlo in molecole piú complesse o in oggetti solidi piú grandi. La prima ipotesi implicherebbe che la formazione di pianeti giganti debba essere rapida o rara, mentre per il secondo scenario le implicazioni sui tempi scala della formazione planetaria sarebbe meno ovvia.

- Nel capitolo 5 un'altra fondamentale proprietá dei dischi é stata investigata con i modelli DALI, ovvero la distribuzione di densitá superficiale del gas $\Sigma_{\rm gas}$. Per comprendere l' evoluzione dei dischi, l'importanza relativa dei vari processi coinvolti in essa e la formazione dei pianeti, sarebbe cruciale costringere $\Sigma_{\rm gas}$ in maniera siolida dalle osservazioni. Questo capitolo si domanda se i profili radiali delle righe del ^{13}CO, come quelli osservati recentemente con

ALMA, possano essere utilizzati per derivare il profilo di densitá superficiale del gas. Paragonando i risultati ottenuti con i modelli DALI, troviamo che i profili radiali del ^{13}CO seguono i profili di densitá nella zona intermedia del disco. L'emissione cala a raggi molto piccoli a causa dello spessore ottico e nelle zone esterne del disco, a grandi raggi, a causa del freeze-out e del fatto che il self-shielding é inefficiente.

- Nel capitolo 6 il network chimico in DALI é stato espandso con l' aggiunta della chimica semplificata del deuterio in modo da poter simulare le righe del HD. L'obiettivo é quello di esaminare la robustezza del HD come tracciante della massa dei dischi, in particolare l'effetto della massa del gas e della estensione veritcale del disco sulle righe infrarosse dell'HD. Troviamo che la determinazione della massa basata sul HD ha un'incertezza moderata. Osservazioni del HD dovrebbero essere quindi considerate come un importante obiettivo scientifico per future missioni nel lontano infrarosso, come ad esempio SPICA.

Le conclusioni principali di questa tesi sono:

1. La fotodissociazione selettiva degli isotopologi del CO deve essere considerata nei modelli quando si simula l'emissione degli isotopologi rari. Altrimenti le righe di emissione del C^{18}O potrebbero essere sovrastimate e le masse del gas sottostimate fino a un ordine di grandezza o piú.

2. La massa di gas nei dischi puó essere misurata combinando l'intensitá integrata delle righe del ^{13}CO e del C^{18}O, anche se con incertezze non trascurabili, fino a due ordini di grandezza per dischi molto massivi.

3. Le masse del gas nei dischi in Lupus misurate dall'emissione del CO risultano essere molto basse, spesso minori di una massa di Giove, e le frazioni globali di massa del gas rispetto alla massa della polvere oscillano tra 1 e 10. Questo puó essere interpretato come rapida perdita di gas da parte del disco, oppure come rapida evoluzione chimica.

4. La forma della distribuzione superficiale di densitá nei dischi puó essere caratterizzata da osservazioni spazialmente risolte di ^{13}CO, se lo spessore ottico, il freeze-out e il self-shielding sono considerati propriamente nei modelli.

5. L'esmission del HD nel lontano infrarosso puó essere usata per determinare la massa dei dischi con una moderata incertezza che dipende principalmente dalla struttura verticale del disco. Questo tipo di osservazioni dovebbe essere considerato come un importante obiettivo scientifico per future missioni nel lontano infrarosso

Il quesito sulla massa gassosa dei dischi protopolanetari rimane irrisolto. Gli isotopologi del CO sono ancora dei promettenti candidati come traccianti della massa dato che la loro rilevazione é routine per ALMA, ma hanno bisogno di essere calibrati. Questa tesi mostra che il processo di fotodissociazione selettiva é importante per una buona interpretazione degli isotopologi del CO come traccianti di massa. Tuttavia, la fotodissociazione, almeno per il caso di TW Hya e probabilmente per altri dischi, non é il fenomeno principalmente responsabile delle righe di emissione cosí tenui osservate negli isotopologi del CO. D'altra parte, la riduzione dell'abbondanza di carbonio in forma gassosa, che deve ancora essere investigata in maniera piú precisa, potrebbe esserne la causa principale. Dove va a finire il carbonio? La rilevazione di molecole leggermente piú complesse, come ad esempio gli idrocarburi C_2H e c-C_3H_2, potrebbe essere una soluzione per la calibrazione delle masse in gas derivate dal CO. Un'altra opzione é quella di allargare il campione di dischi in cui il [CI] é stato rilevato e ció permetterebbe di determinare l'abbondanza di carbonio volatile negli strati superficiali del disco. Infine, se la principale transizione rotazionale dell'HD potrá essere osservata a risoluzione spettrale abbastanza alta con SPICA, la sua rilevazione fornirá una misura della massa dei dischi indipendente dal CO.

Determinare la massa totale dei dichi é una sfida, ma é cruciale tentare di risolvere questo enigma dato che essa é una delle proprietá fondamentali che bisogna constringere per poter comprendere come i pianeti si formano, a partire dal nostro pianeta Terra fino all'immensa varietá di esoplaneti osservati attorno ad altre stelle.

LIST OF PUBLICATIONS

Refereed Publications

1. *New insights into the nature of transition disks from a complete disk survey of the Lupus star forming region*
   van der Marel, N., Williams, J.P., A., Ansdell, M., Manara, C.F., **Miotello, A.**, Tazzari, M., Testi, L., Hogerheijde, M., Bruderer, S., van Terwisga, S.E., van Dishoeck, E.F., (2018) accepted for publication in the Astrophysical Journal.

2. *Physical properties of dusty protoplanetary disks in Lupus: evidence for viscous evolution?*
   Tazzari, M., Testi, L., Natta, A., Ansdell, M., Carpenter, J., Guidi, G., Hogerheijde, M., Manara, C.F., **Miotello, A.**, van der Marel, N., van Dishoeck, E.F., Williams, J.P., (2017) Astronomy & Astrophysics, 606, A88.

3. *Far-infrared HD emission as a measure of protoplanetary disk mass*
   (Chapter 6)
   Trapman, L., **Miotello, A.**, Kama, M., van Dishoeck, E.F., Bruderer, S., (2017) Astronomy & Astrophysics, 605, A69.

4. *An ALMA survey of protoplanetary disks in the σ Orionis cluster*
   Ansdell, M., Williams, J.P., Manara, C.F., **Miotello, A.**, Facchini, S., van der Marel, N., Testi, L., van Dishoeck, E.F., (2017) Astronomical Journal, 153, 240.

5. *ALMA unveils rings and gaps in the protoplanetary system HD 169142: signatures of two giant protoplanets*
   Fedele, D., Carney, M., Walsh, C., **Miotello, A.**, Klaassen, P., Bruderer, S., Henning, T., van Dishoeck, E.F., (2017) Astronomy & Astrophysics, 600, A72.

6. *Lupus disks with faint CO isotopologues: low gas/dust or high carbon depletion?*
   (Chapter 4)
   Miotello, A., van Dishoeck, E.F., Williams, J.P., Ansdell, M., Guidi, G., Hogerheijde, M., Manara, C.F., Tazzari, M., Testi, L., van der Marel, N., van Terwisga, S., (2017) Astronomy & Astrophysics, 599, A113.

7. *Determining protoplanetary disk gas masses from CO isotopologues line observations (Chapter 3)*
   Miotello, A., van Dishoeck, E.F., Kama, M., Bruderer, S., (2017) Astronomy & Astrophysics, 594, A85.

8. *ALMA survey of Lupus protoplanetary disks. I. dust and gas Masses*
   Ansdell, M., Williams, J.P., van der Marel, N., Carpenter, J., Guidi, G., Hogerheijde, M., Mathews, G.S., Manara, C.F., **Miotello, A.**, Natta, A., Oliveira, I., Tazzari, M., Testi, L., van Dishoeck, E.F., van Terwisga, S.E., (2016) The Astrophysical Journal, 828, 46.

9. *Volatile-carbon locking and release in protoplanetary disks. A study of TW Hya and HD 100546*
   Kama, M., Bruderer, S., van Dishoeck, E.F., Hogerheijde , M., Folsom, C.P., **Miotello, A.**, Fedele, D., Belloche, A., Güsten, R., Wyrowski, F., (2016) Astronomy & Astrophysics, 592, A83.

10. *Evidence for a correlation between mass accretion rates onto young stars and the mass of their protoplanetary disks*
    Manara, C.F., Rosotti, G., Testi, L., Natta, A., Alcalá, J.M., Williams, J.P., Ansdell, M., **Miotello, A.**, van der Marel, N., Tazzari, M., Carpenter, J., Guidi, G., Mathews, G.S., Oliveira, I., Prusti, T., van Dishoeck, E.F., (2016) Astronomy & Astrophysics, 591, L3.

11. *Resolved gas cavities in transitional disks inferred from CO isotopologs with ALMA*
    van der Marel, N., van Dishoeck, E.F., Bruderer, S., Andrews, S.M., Pontoppidan, K.M., Herczeg, G.J., van Kempen, T., **Miotello, A.**, (2016) Astronomy & Astrophysics, 585, A58.

12. *Protoplanetary disk masses from CO isotopologue line emission*
    (Chapter 2)
    Miotello, A., Bruderer, S., van Dishoeck, E.F., (2014) Astronomy & Astrophysics, 572, A96.

13. *Grain growth in the envelopes and disks of Class I protostars*
    Miotello, A., Testi, L., Lodato, G., Ricci, L., Rosotti, G., Brooks, K., Maury, A., Natta, A., (2014) Astronomy & Astrophysics, 567, A32.

14. *Evidence of photoevaporation and spatial variation of grain sizes in the Orion 114-426 protoplanetary disk*
    Miotello, A., Robberto, M., Potenza, M.A.C., Ricci, L., (2012) The Astrophysical Journal, 757, 78.

CURRICULUM VITAE

I was born on July 22$^{\mathrm{nd}}$ 1988 to Paola Pignoloni and Roberto Miotello in Gallarate, Italy. For the first 20 years of my life my home town has been Arsago Seprio, a small village in northern Italy. There I attended primary and secondary school, while I went to high school at Liceo Scientifico "Leonardo da Vinci" in the nearby town of Gallarate. I have always been particularly passionate about mathematics and science, but also about art, philosophy and sport. My decision to study Physics at the Universita' degli Studi di Milano was lead by the certainty that this was the subject where I would have learned the most.

Already at the end of my Bachelor my interest was caught by Astrophysics. Under the supervision of Dr. Marco A.C. Potenza and Dr. Massimo Robberto (STScI) I carried out my Bachelor's degree Thesis on HST (Hubble Space Telescope) observations of a protoplanetary disk in the Orion Star Forming Region to study its dust particles properties. This project was completed during a Summer Studentship program at STScI in 2011 and ended up in my first publication in 2012. I carried out my Master studies in Physics, with a focus on Astrophysics, at the Universita' degli Studi di Milano. My Master degree Thesis on dust grain growth in Young Stellar Objects was supervised by Prof. Giuseppe Lodato and Dr. Leonardo Testi (ESO) and was mainly carried out at ESO in Garching. There, I met Prof. Ewine F. van Dishoeck for the first time, who, not much later, offered me a PhD position at the Leiden Observatory. I accepted that position and started my PhD in June 2013 as that would have been the best opportunity to learn about the gas content in protoplanetary disks.

In the following four and a half years, during my PhD, I have carried out my research on the molecular gas, in particular carbon monoxide isotopologues, in protoplanetary disks with the aim of determining their total mass. In practice, I have learned about physical-chemical modelling of disks and run many simulations. Toward the end of my PhD I started working with observations, specifically with ALMA data in the Lupus star-forming region and I compared them with my models. The results are presented in this thesis. The different projects have been presented to conferences and workshops all over the world. I worked for the first year of my PhD at the Max Planck Institute for Extraterrestrial Physics in Garching (Germany) and the following three years at Leiden Observatory. There I had the opportunity to train Master's students for their Master Colloquia and to help in their evaluation. Furthermore, I had the pleasure to supervise the M.Sc. project of Leon Trapman, which became one of the Chapters of this thesis. In these four and a half years I also bore three marvellous children.

In October 2017 I have started a three-year postdoctoral position as ESO Research Fellow in Garching (Germany).

ACKNOWLEDGEMENTS

Quoting G. K. Chesterton, *I would maintain that thanks are the highest form of thought, and that gratitude is happiness doubled by wonder*. I am indeed sincerely grateful for all what happened in the past four and a half years, which was made possible by many people, many more than those I can list here.

I would like to start by thanking those people who have supervised my work day after day. Simon, I had the privilege to start my PhD learning from you how to model a protoplanetary disk and that one should never stop to run checks: you will always be my coding guru. Mihkel, you have accompanied me as an older brother would do and I appreciated how you tolerated me also as office mate; furthermore, you will always be the first Estonian I have met. But more than anybody else I want to express my gratitude to the woman who managed to drag me far from the Alps, introduced me to Astrochemistry, challenged me to always go one step forward, supported me with a lot of little practical things, and made me reach achievements I would have never thought to reach (like swimming with the sharks).

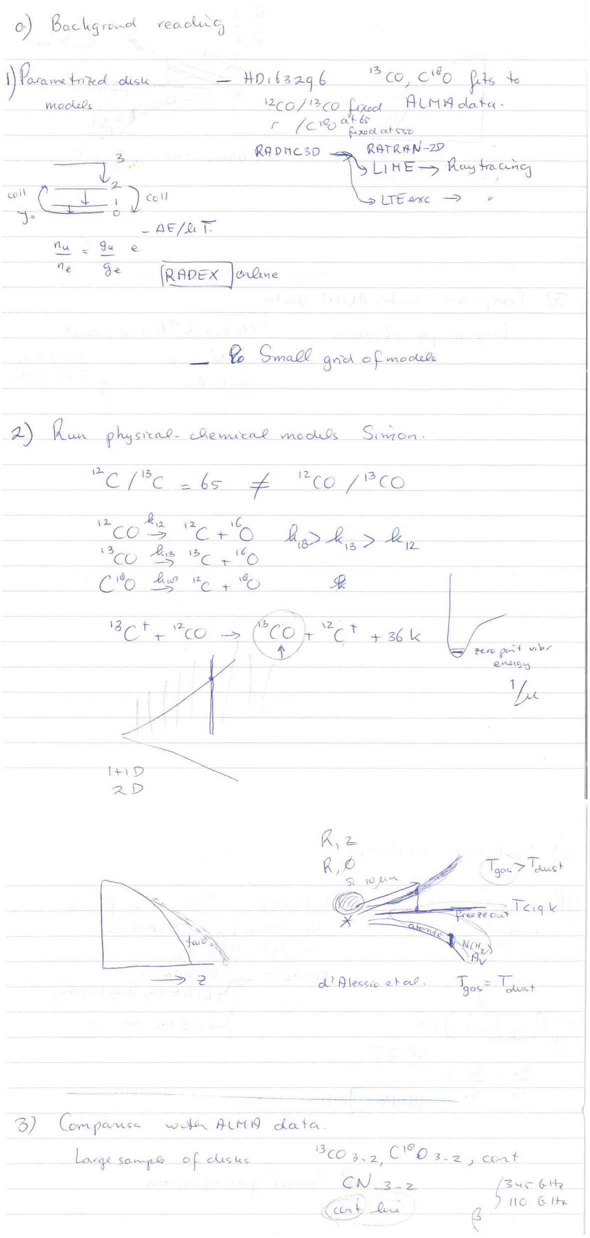
The Sterrewacht has accompanied me, supported me and made me grow as a scientist and as a person. I have always felt challenged to reach for the stars and reassured that I could make it. This went through my fellow PhD students, the postdocs, the faculty members, in particular Elena and Xander, as well as the PBC committe and the dedicated support staff, who has always made my life easier. More specifically, I would like to mention the computer group lead by Erik: you are probably the best IT in the world. Also, a great thanks goes to the Allegro group: Luke, Ciriaco, Michiel, Daniel, Carmen, Liz, your support with ALMA data has been one of the most precious things.

In Leiden I have been part of a fantastic and unique group, which helped me to complete my PhD and, most importantly, made it fun. Its composition evolved durning the years and the number of people to acknowledge is very large. Let me start with my office mates. Catherine, you have been a real inspiration for me: I like that you are a tough woman, smart and hard worker, but most of all I enjoyed your Irish accent and your sarcasm. I have learned much from you, from astrochemistry to making fresh coffee with a french press. Xiaohu, sharing office with you showed me the beauty of cultural diversity and I thank you for leaving me your desk and your

good luck plant. Arthur, you are simply remarkable! Thanks for teaching me many things, from coding to dutch slang, for your loud and contagious laugh and for being in the office with me early in the morning. Sierk, your encyclopaedic knowledge has alway impressed me and I have enjoyed learning about dutch culture from you. Lukasz, thanks to you I can claim I know some Polish words and that I shared the office with the second best coffee maker of Poland: I enjoyed your fresh enthusiasm about everything, from the starry sky, to science, to the mountains. Now it is time for the best room mates at conferences. Paola, you have been a true friend to me: I miss our chats and our coffees and I hope that we will work again together in the future. Do not forget to organise that conference in Cartagena! Merel, how would I do without you: you are so accountable! Thanks for all your human and practical support, I will miss that. Then my gratitude goes also to Nienke, for welcoming me in the group, Maria, for her strength, Nadia, for her delicious cakes, Agata, for being a fellow PhD-mother, to Irene per la sua simpatia, Christian for his enthusiasm, and Koju for his optimism. I would not have learned so much without all the postdocs, Vienney, Alvaro, John, Magnus, Alan, Daniel, Joe and Kenji: thanks for being there for me when I needed it. Thanks to Niels and Nico: we started together and I have been so happy to have you there during these years. I owe a lot to Leon, the first Master student I have supervised: you have done such a good job that now I am spoiled! Thanks for contributing to my PhD thesis. Finally, a warm grazie to the Italian members of the group, Davide, Stefano and Paolo. I am grateful to have had you as travel companions: your were there to support me when the motivation was going down, and to rejoice with me for the beautiful things happening. Of course my PhD thesis would not have been so pretty without my favourite designer, Laura.

I have enjoyed very much being part of the Lupus collaboration, both from a scientific and human point of view. Jonathan, thanks for leading our team in such a friendly way, for going often against the grain and for hosting us in your beautiful house in Hawaii. Megan, it was great meeting you and visiting you: thanks for showing me around in Hawaii and for letting me know only one year later that I had indeed swum with the sharks. Marco, we know each other since we were freshmen and working with you as a collaborator has been incredible. Last, but not the least, thanks to Leonardo and Antonella for your curiosity, your love for the data and your mentoring.

I would like to thank my parents and my family for always supporting me and for showing their interest in my research. To conclude, I would like to show my gratitude to the four most important people in my life. Carlo, without your tireless backing and cheering I would have never reached the end of this PhD. Caterina, Ambrogio, and Monica, you have been the most beautiful gifts of these last four years: this PhD without you would have been definitely much less fun!



0) Background reading

1) Parametrized disk models — HD163296 ^{13}CO, $C^{18}O$ fits to ALMA data.

$^{12}CO/^{13}CO$ fixed at 65

r / $C^{18}O$ fixed at 550

RADMC3D → RATRAN-2D

→ LIME → Ray tracing

→ LTE exc → "

coll

coll

3

2

1

0

J=

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-\Delta E/kT}$$

$\boxed{\text{RADEX}}$ online

— to Small grid of models

2) Run physical-chemical models Simon.

$$^{12}C/^{13}C = 65 \neq {}^{12}CO/^{13}CO$$

$$^{12}CO \xrightarrow{k_{12}} {}^{12}C + {}^{16}O \qquad k_{18} > k_{13} > k_{12}$$

$$^{13}CO \xrightarrow{k_{13}} {}^{13}C + {}^{16}O$$

$$C^{18}O \xrightarrow{k_{18}} {}^{12}C + {}^{18}O$$

$$^{13}C^+ + {}^{12}CO \rightarrow {}^{13}CO + {}^{12}C^+ + 36\,K$$

zero point vibr energy

$1/\mu$

1+1D

2D

R, z

R, ϕ

Si 10 μm

$T_{gas} > T_{dust}$

$T < 19\,K$

freeze out

atomic

$N(H_2)$

A_V

faces

→ z

d'Alessio et al.

$T_{gas} = T_{dust}$

3) Comparison with ALMA data.

Large sample of disks

^{13}CO 3-2, $C^{18}O$ 3-2, cont

CN 3-2

cont line

345 GHz

110 GHz

B

Figure 12.1: Almost everything was there since the beginning - Pen and paper initial overview of this PhD Thesis by Ewine.