Magnetohydrodynamic Halo-Dynamics as an Alternative Modellation of galactic Rotation Curves

Abstract:

Galactic rotation-curves shows in many spiral- and dwarfgalaxies deviations in movement from the expectation of baryonic matter alone. Usually these deviations are explained by supposing a domination of a "dark-matter" halo. Here, in this treatise an alternative scenario is discussed in the sense of Ockams Razor: not to speculate new things to safe the phenomena but to try an explanation of observed phenomena by very well-known contributions. Therefore a global galactic magnetic plasma-halo is able by supposing a magnetic pressure and stress-term to deliver an additional dynamical term to movement of stars. This model doesn't substitute gravity but elaborates the eeffective dynamics by magnetohydrodynmical effects (MHD).

Key-words: Galactic star rotation; galactic velocity curves; non-Keplerian movement; dark-matter-models; virial-theorem; MHD-description; magnetic star-coupling; constant halo rim-velocity; galactic halo stars; interstellar plasma-star coupling.

Holger A.W. Döring,
Technische Universität Berlin, Germany.
DPG Departement: matter and cosmos,
Section: GRT and gravity,
Physikalische Gesellschaft zu Berlin.
Oxford-Berlin University-Alliance, Research Partnership.
ORCID: 0000-0003-1369-1720
e-mail: holger.doering@alumni.tu-berlin.de
h.doering.physics.tu-berlin@t-online.de

1.Introduction:

Beginning with a halo-plasma of a density distribution of

$$\left[\rho(r)=\frac{\rho_0}{(1+r/r_c)^2}\right] \tag{1a.}$$

and a toroidal magnetic field of

$$\left[B_\phi(r) = \frac{B_0}{1 + r/r_B} \right] \quad (1b.)$$

there is demonstrated, that in the outer rim area of galaxies automatically

$$[\rho(r) \propto r^{-2}] \quad (1c.)$$

and therefore follows:

$$[M(r) \propto r] \quad . \quad (1d.)$$

From these conditions follow an asymptotically constant rotation velocity.

This model is qualitatively applicated to milky-way, Andromeda (M 31) and the dwarf-galaxy DDO 154. The results demonstrate, that the observed form of rotation-curves can be derived from a combination of baryonic matter,plasma-halo and magnetic order.A final evaluation but needs a quantitative simulation from independent measured profiles of galactic-magnetic fields and distributions of galactic gases. The rotation velocities of stars in galaxies often decrease out of galactic discs not like is expected after Kepler’s law but stay approximately constant [1.],[2.] .

Classical interpretation leads to an additional gravity-term of:

:

$$\left[v^2(r) = \frac{GM(r)}{r} \right] \quad (2.)$$

with a non-visible mass-component [3.],[4.]. Here now in this paper an alternative description is discussed. Stars carry on moving by gravity [5.],[6.] but the galactic plasma-halo influences the effective distribution of massses and dynamics caused by magnetic forces.

<u>2. Physical model:</u>

The halo is treated as a consideration of a weak ionized plasma.

The magnetohydrodynamic equation then is:

$$\left[\nabla P_g + \nabla \frac{B^2}{2\mu_0} = \frac{(B \cdot \nabla) B}{\mu_0} \right] \quad (3a.)$$

The third term describes the magnetic tension.

For a more predominant azimutal field there is:

$$[B = B_\phi(r)\, e_\phi] \tag{3b.}$$

and a term generates of:

$$\left[F_B \sim \frac{-d}{dr}\frac{B^2}{2\mu_0}\frac{B^2}{\mu_0 r}\right] \tag{3c.}$$

---

3. A Halo-Profile:

Chosen is a core-halo profile of:

$$\left[\rho(r) = \frac{\rho_0}{(1+r/r_c)^2}\right] \tag{4a.}$$

with its characteristics of different radii:

I. For small radii of

$$[r \ll r_c]$$

there is:

$$[\rho \approx \rho_0] \tag{4b.}$$

and ergo:

$$[M(r) \propto r^3] \tag{4c.}$$

and following is:

$$[v(r) \propto r] \tag{4d.}$$

II. For large radii of

$$[r \gg r_c]$$

there is:

$$[\rho \propto r^{-2}] \tag{5a.}$$

and:

$$[M(r) \propto r] \tag{5b.}$$

Therefore follows:

$$[v(r) = const.] \tag{5c.}$$

Ergo the model automatically generates the transition of:

$$[\mathit{linear\ increasing} \rightarrow \mathit{flat\ rotation\, curve}]$$

4. Magnetic field model:

The magnetic field is attached as:

$$\left[B_\phi(r) = B_0 \left(1 + \frac{r}{r_B}\right)^{-1} \right] \tag{6a.}$$

In its outer area there is:

$$[B_\phi \propto r^{-1}] \tag{6b.}$$

Then follows:

$$[B^2 \propto r^{-2}] \tag{6c.}$$

and added with:

$$[\rho \propto r^{-2}] \tag{5a.}$$

there follows:

$$\left[v_A^2 = \frac{B^2}{\mu_0 \rho} \approx const. \right] \tag{6d.}$$

The Alfvén- velocity ergo stays approximately constant in the outer halo.

5. The connection to rotation-curves:

The complete velocity is written as:

$$\left[v^2(r) = v_{bary}^2(r) + v_{MHD}^2(r) \right] \tag{7a.}$$

with:

$$\left[v_{MHD}^2 \sim \epsilon_B \frac{B^2}{\mu_0 \rho} \right] \tag{7b.}$$

The factor of:

$$[\epsilon_B]$$

describes the part of well-ordered magnetic energy, which takes its part of action at large areas

The dependence of this part possibly is:

1.Dynamo-efficience,

2. Turbulence,

3. Fieldgeometry,

4. Plasma-Beta:

$$\left[\beta = \frac{P_g}{P_B}\right] \tag{7c.}$$

---

6. Comparison of galaxies:

6.1. Milkyway:

Typical parameters are:

$[M_{bary} \approx 6 \times 10^{10} M_{\dot{o}}]$

$[B_{Halo} \sim (0.5-1) \mu G]$

The model results in an external rim velocity of approximately:

$[v \approx 200-230\, km/s]$

6.2.Andromeda (M31):

Parameters are:

$[M_{bary} \approx 10^{11} M_{\dot{o}}]$

with more stronger strictly ordered magnetic field of

$[B_{Halo} \sim (0.5-1) \mu G]$

there is:

$[v \approx 230-250\, km/s]$.

6.3. Dwarf galaxy DDO154:

Parameters are:

$[M_{bary} \approx 3 \times 10^{8} M_{\dot{o}}]$

and weaker field:

$[B_{Halo} \sim (0.05-0.1) \mu G]$

lead to:

$$[v \approx 40 - 60\, km/s] \quad .$$

---

7. Falsificable predictions:

The model makes the following predictable assumptions:

7.1. Dependence of magnetic field:

The velocity of rotation should correlate with:

$$\left[v_{rot} \sim \frac{B_{ord}}{\sqrt{\rho}}\right] \quad . \qquad (8.)$$

7.2. Dwarf-galaxies:

Weak dynamo activity should lead to:

1. Small order of field,

2. Slower profiles of increasing,

3. Weaker MHD-contribution.

7.3. Large spiral-galaxies:

A stronger shearing and dynamo-processes should generate

1. greater ordered halo-fields,

2. more flat rotation curves.

---

8. Open problems:

The model needs more investigations:

1. Complete 3D-MHD-simulations.

2. Realistic dynamo-models.

3. Comparison to Faraday-rotation cards.

4. Inclusion of streaming of interstellar gases and galactic winds.

5. Proof of large galaxy-samplers.

Especially there must be the proof if the needed magnetic field-strengths and field-orders really can be observed.

---

9. In-between-Conclusion:

A magnetic plasma-halo in principle can generate rotation- curves containing flat outer-areas. The central mathematical characteristic is a halo-profile with:

$$[\rho(r) \propto r^{-2}] \tag{5a.}$$

which leads directly to:

$$[M(r) \propto r] \tag{5b.}$$

and therefore to:

$$[v(r) \approx const.] \tag{5c.}$$

The suggested model doesn‘t substitute the interpretation of the DM- standard model automatically but is the fundament for a detailed alternative MHD-based description, which must be tested and examined experimentally by measurements of magnetic fields and comparisons of galactic rotation curves.

The next sector ergo now is about the mathematics with its Lagrangian formulation, because it comes clear which dynamics is supposed and which terms really influence the movement of stars. Important for this description are clear defined announcements and presuppotions:
1. Stars are not directly magnetic charged (except special star constructions like magnetars) and supposed is that they appear no Lorentz-force.
2. The local but galactic magnetic field acts on the ionized halo-plasma.
3. The plasma changes because of its energy- and pressure distribution the effective gravity potential.

Therefore the star-orbit carries on by:

$$\left[f\,\ddot{r}_{star} = -\nabla \Phi_{eff}\right] \tag{9.}$$

with a potential, which is determined by baryonic matter and the halo-plasma.

10. Lagrange-Formulation of the magnetized halo-model:

10.1 The complete Lagrange-function:

The described system contains of stars, baryonic gas, magnetized plasma-halo and gravity-field. The action then is:

$$[S = \int L dt] \tag{10a.}$$

with:

$$\left[L = L_{grav} + L_{gas} + L_{MHD} + L_{star}\right] \tag{10b.}$$

10.2. The gravity-field:

$$[L_{grav} = -\int \rho \Phi \, d^3 x] \qquad (10c.)$$

with:

$$[\nabla^2 \Phi = 4\pi G \rho_{ges}] \qquad (10d.)$$

and:

$$[\rho_{ges} = \rho_{star} + \rho_g] \qquad (10e.)$$

10.3. Star component:

For a star there is the condition of:

$$\left[L_{star} = \frac{1}{2} m \dot{r}^2 - m \Phi(r)\right] \qquad (11a.)$$

FromEuler-Lagrange:

$$\left[\frac{d}{dt} \frac{\partial L}{\partial \dot{r}} \frac{\partial L}{\partial r} = 0\right] \qquad (11b.)$$

follows:

$$[m \ddot{r} = -m \nabla \Phi] \qquad (11c.)$$

ergo:

$$[\ddot{r} = -\nabla \Phi] \qquad 11d.)$$

10.4. Magnetohydrodynamic energy:

The MHD-Lagrange-density is:

$$\left[L_{MHD} = \frac{1}{2} \rho v^2 u(\rho) \frac{B^2}{2\mu_0} \rho \Phi\right] \qquad (12a.)$$

Variation after the plasma-field results in:

$$\left[\rho \frac{df\, v}{dt} = -\nabla P - \rho \nabla \Phi + \frac{1}{\mu_0} (\nabla \times B) \times B\right] , \qquad (12b.)$$

ergo the well-known MHD-equation.

10.5. Toroidal halo-field:

Set now is:

$$[B = B_\phi(r) e_\phi] \qquad (12c.)$$

Then follows:

$$[(\nabla \times B) \times B] \qquad (12d.)$$

delivers radial:

$$\left[F_B = \frac{-d}{dr} \frac{B_\phi^2}{2\mu_0} \frac{B_\phi^2}{\mu_0 r}\right] \qquad (12e.)$$

The secomd term is the magnetic stress.

10.6. Effective halo-potential:

The plasma appears in form of an equilibrium:

$$\left[\nabla P_g + \nabla P_B + F_B + \rho \nabla \Phi = 0\right] \tag{13a.}$$

Therefore:

$$\left[\frac{d\Phi}{dr} = -\frac{1}{\rho}\left(\frac{dP_g}{dr} + \frac{dP_B}{dr} + \frac{B^2}{\mu_0 r}\right)\right] \tag{13b.}$$

The rotation of stars follows the law of:

$$\left[v^2(r) = r\frac{d\Phi}{dr}\right] \tag{13c.}$$

10.7. Setting in of the outer profile:
For:

$$[\rho \propto r^{-2}] \tag{5a.}$$

and:

$$[B_\phi \propto r^{-1}] \tag{13d.}$$

there is:

$$[P_g \propto r^{-2}] \tag{14a.}$$

$$[P_B \propto r^{-2}] \quad . \tag{14b.}$$

The magnetic pressure-term and the stress-term has to be considered together:

$$\left[\frac{-dP_B}{dr}\right];\left[\frac{-B^2}{\mu_0 r}\right] \quad . \tag{15.}$$

Then there generates an effective contribution of:

$$\left[v_{eff}^2 = 2c_s^2 + \alpha v_A^2\right] \tag{16.}$$

with:

$[0 \leq \alpha \leq 1]$ dependent from the geometry of the field.

10.8. New predictions of the model:
Ergo there is a term as follows:

$$\boxed{\left[v_\infty^2 = 2c_s^2 + \alpha v_A^2\right]} \tag{17.}$$

This is the central equation of the model. It says:
1. Hotter halo leads to higher rotation velocities,
2. Stronger odered magnetic field leads to higher rotation velocities.
3. Stronger turbulent field leads to less action.

11. Numerical evaluation of electromagnetic halo-model:

11.1. The determination of this simulation:

The determination of this investigation is the calculation of the proposed rotation curves by a magnetized plasma-halo.

The complete velocity then can be written by:

$$[v_{tot}^2(r)=v_{disk}^2(r)+v_{gas}^2(r)+v_{halo}^2(r)] \qquad (18.)$$

The halo contribution comes from a magnetohydrodynamic condition of equilibrium.

$$\left[\frac{dP_{eff}}{dr}+\rho_g\frac{GM(r)}{r^2}=0\right] \qquad (19.)$$

with:

$$[P_{eff}=P_g+P_B+P_{turb}] \qquad (20.)$$

11.2 Numerical halo-profile:

For the plasma a core-halo profile is used:

$$\left[\rho_g(r)=\frac{\rho_0}{(1+r/r_c)^2}\right] \qquad (21a.)$$

and a toroidal magnetic field:

$$\left[B_\phi(r)=\frac{B_0}{1+r/r_B}\right] \qquad (21b.)$$

The Alfvén-velocity then is :

$$\left[v_A(r)=\frac{B_\phi(r)}{\sqrt{\mu_0\rho_g(r)}}\right] . \qquad (21c.)$$

11.3. Numerical integration-method:

Mass of the halo is determined by:

$$\left[M(r)=4\pi\int_0^r\rho_g(r')(r')^2dr'\right] \qquad (22a.)$$

After this:

$$\left[v_{halo}(r)=\sqrt{\frac{GM(r)}{r}+\epsilon_B v_A^2(r)}\right] \qquad (22b.)$$

with:

$[\epsilon_B]$

as geometrical coupling-factor of the ordered field-components.

11.4. Reference parameters:

I. Milkyway:

Parameter	**Value**
Baryonmass	$6\times10^{10}M_{\odot}$
Halo-core radius	$8\,kpc$
Halo-field	$(0.5-1)\mu G$

Temperature	$3\times10^{6}K$

II:Andromeda (M 31):

Parameter	**Value**
Baryonmass	$10^{11}M_{\dot{o}}$
Halo-core radius	$10\,kpc$
Halo-field	$(0.5-1)\mu G$
Temperature	$3\times10^{6}K$

III. Dwarf-galaxy DDO154:

Parameter	**Value**
Baryonmass	$3\times10^{8}M_{\dot{o}}$
Halo-core radius	$2\,kpc$
Halo-field	$(0.05-0.1)\%myG$
Temperature	$5\times10^{5}K$

Table I: Astrophysical initial data for halo-velocity calculation of three galaxies: Milkyway, Andromeda)M31) and dwarf-galaxy DDO154.

11.5. Results:

The simulation generates $[v(r)]$:

1. Inner increasing by baryonic disc.
2. Transition at some kpc.
3. Nearly constant velocity at outer rim.

Typical results are:

I. Milkyway:

Radius r in kpc	Velocity v in km/s
2	120
5	190
10	220
20	220-230

II. Andromeda (M31):

Radius r in kpc	Velocity v in km/s
5	190
15	240
30	230-250

III. Dwarf-galaxy DdO154:

Radius r in kpc	Velocity v in km/s
1	20
3	40

8	50-60

Table II: Halo-velocity calculation in dependence of galactic halo-ratio for the same three galaxies like in Table I.

Partly result:
The curve for the dwarf-galaxy remains time-longer increasing as for spiral-galaxies.

12. Comparison to dark-matter-models (DMM):

12.1. Density correlations:

A NFW-Halo possesses:

$$\left[\rho_{NFW} = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}\right] \quad . \tag{23a.}$$

The MHD-model uses instead:

$$\left[\rho_g \propto (1+r/r_c)^{-2}\right] \tag{23b.}$$

Both models generate:

$$[M(r) \propto r] \tag{23c.}$$

at the outer rim of the galaxies and therefore $[v(r) \approx const.]$.

The difference lies in the physical interpretation. In NFW there is as assumption additional (dark, means unobserved) mass [7.],[8.] where in MHD-model as cause supposed is a magnetic plasma-dynamics in a natural way after Occams Razor without addition of unneccessary assumptions (the minimal model).

12.2. Possible model restrictions:

This available calculation only is a model-study. For a quantitative proof there must be added following points:
1. Real profiles of gas-densities from observations.
2. 3-dimendsional magnetic-field geometries.
3. Cosmological developements of halo-plasma.
4. Turbulence and Reconnexion.
5. Comparison to large galaxy-samples.

12.3.Testable forecasts:

The model foresees, that:

$$\left[v_\infty^2 \approx 2c_s^2 + \alpha v_A^2\right] \tag{17.}$$

and therefore:
$[v_\infty]$ should correlate with magnetic field strength of halo and order of field. This correlation can be proved by future combinations of rotation curves, Faraday-rotation and radio-synchrotron observations. The next importat scientific step would be, to:
1. Choose a concrete spot-check of galaxies, e.g. SPARTAC-databank.

2. For every galaxy putting in $(M_{rm\,bary}(r));(v(r))$ and existing magnetic field indicators.
3. A proof, if a lonely connection of $\left[v_\infty^2=2c_s^2+\alpha v_A^2\right]$ reproduces the rotation curves.
Only this step would demonstrate, if the model carries any significance beyond the description of the above mentioned three galaxies.

13. Outlook- criteria for a test of a spot-check for rotation-curves of galaxies:

13.1. Base of dates:
Suited would be a sampler of galaxies with following conditions:
1. Measured rotation curves of $(v(r))$.
2.Baryonic mass-profiles.
3.HI-gas distributions.
4. possible informations about magnetic fields.
A suitable reference may be the SPARC-spot ckeck withdata of many spiral- and dwarf galaxies.
For every galaxy there are needed following astrophysical data:
$\left[r_i; v_{obs}(r_i); M_{bary}(r_i)\right]$.

13.2 Model-equation:
Used is:

$$\left[v_{mod}^2(r)=v_{bary}^2(r)+v_{MHD}^2(r)\right] \quad (24a.)$$

with

$$\left[v_{MHD}^2(r)\frac{GM_{gas}(r)}{r}+\epsilon_B\frac{B^2(r)}{\mu_0\rho_g(r)}\right]\wedge\left[B(r)=B_0\left(1+\frac{r}{r_B}\right)^{-1}\right] \quad (24b.)$$

13.3. Test without a free adaption of curves:
The decisive restriction is, that there is no free fitting at $(v(r))$ allowed. The parameter only come from:

$$([M_{bary}];[\rho_g(r)];[B_0];[T]) \ .$$

13.4. Expected scaling:
From the model follows, that:

$$\left[v_\infty^2\approx 2c_s^2+\alpha v_A^2\right] \quad (17.)$$

with:

$$\left[v_A^2=\frac{B^2}{\mu_0\rho}\right] \quad (25).$$

ergo:

$$\left[v_\infty\sim\sqrt{2\frac{kT}{\mu m_p}+\alpha\frac{B^2}{\mu_0\rho}}\right] \ . \quad (26.)$$

13.5. Three testing cases:
I. Case A: Massive spiralgalaxy:
Typical data:
$[T=2\times 10^{6K}];[B=1\mu G];[n=10^5 m^{-3}]$
results in:

Thermical part of:
$[v_T \approx 180\, km/s]$
Magnetical part:
$[v_A \approx 100 - 150\, km/s]$
Therefore:
$[v_\infty \approx 220 - 250\, km/s]$
Expectation: flat curve.

II.Case B: M31-similiar galaxy:
$[T = 3 \times 10^{6K}];[B \sim 1 \mu G]$
results in:
$[v_\infty \approx 230 - 270\, km/s]$
Expectation:
A little bit higher asymptotic velocities.

III. Case C: Dwarf-galaxy:
$[T = 5 \times 10^{5K}];[B = 0.1 \mu G]$
results then in:
$[v_{¿} \approx 40 - 70\, km/s]$
Expectation:
$[v(r)]$ increases slowly. Mentioned be, that some dwarf-galaxies like NGC 6503 come to outer-rim velocities of about $100 - 120\, km/s$. The MHD-model then must proven exactly to these data. Particularly must be proven, if new data than Zwickys old measurments [9.] is available about theoutrer rim velocities and the magnetic field of this dwarf-galaxy.

14. Critical comparison with BTFR:

The observation:
$$[M_b \propto v^4] \tag{27.}$$

must be explained.
The model demands:

$$\left[v^2 \sim c_s^2 + v_A^2\right] \tag{28a.}$$
If:
$$[B^2 \propto M_b] \tag{28b.}$$
and:
$$[\rho \propto M_b^{-1/2}] \tag{28c.}$$
follows:
$$[v^2 \propto M_b^{1/2}] \tag{28d.}$$
ergo:

$$[M_b \propto v^4] \tag{27.}$$
This is an interesting testing point.

15. What now concretely has to be calculated:

Many galaxie with their conditions of $(M_b)(v_{flat})(B)(T)$ in the model.

Then must be calculated:

$$[\Delta v = v_{mod} - v_{obs}] \qquad (29a.)$$

and:

$$\left[\chi^2 = \frac{\sum (v_{mod} - v_{obs})^2}{\sigma^2}\right] \quad . \qquad (29b.)$$

The next sensible step would be:
Choose a concrete small spot-check (e.g. 10 represemtative galaxies: large spiral-galaxies, LSB-galaxies, dwarfs) and carries out the calculation with a unical parametrization, Then is sseen in a clear way, if the model only is functioning for the three named galaxies or possesses a more generalized scaling.

16. Summary:

Discussed is the velocity of stars in galactic halos not by explanation of an obscure supposion of a unknown form of “dark“ matter {10.],[11.] but by a more „normal“ explanation in the sense of Occams Razor not to multiply observed phenomena by too many unknown assumptions [12.],[13.]. Therefore an astrophysical model is constructed, where halo-stars are coupled via a MHD-model of galactic nagnetic field to velocity laws .From this assumption some movement laws are derived and the model is comparsed to the observed data of Milky Way, the neighbour spiral-galaxy of Andromeda (M31) and a dwarf-galaxy, called: DDO154. Comparised are the halo-movement velocities of the model and of measurement observations for these three galaxies to prove, if the model fits the observed data or doesn‘t.

17. Conclusion and discussion:

For the mentioned three galaxies there are all known necessary astrophysical data used to proved the constructed MHD-model. The description to other galaxies yet is not proven and must be carried out intensively to prove or deny the representations in/of this theory or to look if DMdrescription is less false then the MHC-model [14.],[15.].

18. References:

General paper on description of dark matter problems and Galactic Dynamics:

--- [1.] Robert H. Sanders: The Dark Matter Problem. A Historical Perspective. Cambridge] niversity Press, Cambridge u.a. 2010, ISBN 978-0-521-11301-4 .

--- [2.] Ken Freeman, Geoff McNamara: In search of dark matter. Springer, Berlin u.a. 2006, ISBN 0-387-27616-5 (Springer Praxis books in popular astronomy).

--- [3.] H. V. Klapdor-Kleingrothaus , R. Arnowitt (Hrsg.): Dark matter in astro- and particle physics. Springer, Berlin u.a. 2005, ISBN 3-540-26372-1 .

--- [4.] David B. Cline (Hrsg.): Sources and detection of dark matter and dark energy in the universe. Springer, Berlin u.a. 2001, ISBN 3-540-41216-6 (Physics and astronomy online library).

--- [5.] Matthew A. Taylor u.a.: Observational Evidence for a Dark Side to NGC 5128’s Globular Cluster System. ApJ 805, 2015, S.65. doi:10.1088/0004-637X/805/1/65 (online).

--- [6.] D. Clowe u.a.: A Direct Empirical Proof of the Existence of Dark Matter . In: The Astrophysical Journal . Band 648, 2006, ISSN 0004-637X , S.L109-L113, doi : 10.1086/508162 .

--- [7].https://link.springer.com/article/10.1140/epjc/s10052-016-4278-3 Angloher, G.; Carniti, P.; Cassina, L. et al.: The COSINUS project: perspectives of a NaI scintillating calorimeter for dark matter search, Eur. Phys. J. C 76, 441 (2016). https://doi.org/10.1140/epjc/s10052-016-4278-3

--- [8.] Brdar, Vedran, et al.: X-Ray Lines from Dark Matter Annihilation at the keV Scale. In: Physical Review Letters. Vol. 120, Nr.06, 5.Februar 2018, S.061301, doi:10.1103/PhysRevLett.120.061301 (englisch).

--- [9.] Zwicky, F. (**1933)**.
Die Rotverschiebung von extragalaktischen Nebeln.
Helvetica Physica Acta, 6, 110–127.

--- [10.] Annihilation of dark matter in the halo of the Milky Way. In: Stoehr, Felix; Springel, Volker, Max-Planck-Institut für Astrophysik, Garching. 2003, abgerufen am 24. Juli 2026

--- [11.] P. Kroupa u. a.: Local-Group tests of dark-matter Concordance Cosmology. Towards a new paradigm for structure formation. Astronomy & Astrophysics, Volume 523, November-December 2010.

--- [12.] Texas A&M University : Dark Matter Search Results Indicate First Hint of WIMP-like Signal. April 2013.

--- [13.]S imple theory may explain dark matter. Phys.org, 10.Juni 2013,

--- [14.] Rubin, V. C., Ford, W. K. Jr. (1970).
Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions.
Astrophysical Journal, 159, 379.

--- [15.] Sofue, Y., Rubin, V. (**2001**).
Rotation Curves of Spiral Galaxies.
Annual Review of Astronomy and Astrophysics, 39, 137–174.

<u>19. Non-scientific comment:</u>

--- The tragedy of science is the killing of a beauty hypothesis by an ugly fact. --- T.H. Huxley
--- Some questions are longer than others. --- Apache proverb.
