Luminosity distance vs. proper distance: Cosmological effects from nonlinear electrodynamics

“L’energie sombre un mirage cosmique !?”

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Abstract

By-now photons are the unique universal messengers. Far-away galaxies or quasars are well-known light-emitters. The nonlinear electrodynamics (NLED) description of photon propagation through the weak intergalactic (background) magnetic fields (IGF, Bs) implies a fundamental change in the cosmological redshift, z, ascribed to a distant source in a specific cosmological model. Irrespective of the class of NLED Lagrangians, the effective redshift: $(1+z)|_{\rm eff} = (1+z)\Delta$, $[\Delta \equiv (1+\Phi_e)/(1+\Phi_o)$, $\Phi \equiv 8/3(L_{FF}/L_F)B^2$, $L_F = dL/dF$, $L_{FF} = d^2L/dF^2$, $F \equiv F_{\alpha\beta}F^{\alpha\beta}$, and B the magnetic field strength], is always lower than the standard redshift, but it recovers such limit when the NLED correction $\Delta(\Phi_e, \Phi_o) \longrightarrow 1$. As we do not ever observe proper distances (PD), one can argue that for a given z the observed luminosity distance (LD) of the light-emitting source is different. Observational implications of this finding are potentially far-reaching.

Outline

Interpretation of SNIa observations *alla* Friedmann Model hints at Dark Energy

What SNIa observations tell us about:

- Dimming in SNIa luminosity [1] (thought of as standard candles) $\longrightarrow\longrightarrow$ Universe expansion history changed!
  1. Excluding any potential systematics[a], SNIa data in Hubble diagram (HD): (redshift (z) vs. luminosity distance (LD)) appear over standard Friedmann model limiting curve
  2. SNIa data pile-up around $z \sim 0.5 - 1$ (transition era!)
  3. SNIa observations vs. standard cosmological model $\longrightarrow\longrightarrow$ late-time acelerate transition $\longrightarrow\longrightarrow$ DE!
- z vs. LD (HD): fundamental piece in achieving such conclusion
- z: from absorption lines of SNIa host galaxies

[a] One may be unable to detect, due to dust effects, much more reddened SNIa taking place at much higher redshifts (z), than close-by bluish explosions because simply these late ones are much brighter [2])

Overview on Nonlinear electrodynamics

NLED hints at key changes in HD !

- Unavoidable nonlinear (NL) interaction of GALs/QSRs light with IG *Bs*[a] modifies putative *z* ascribed to a given source!
- To investigate (GALs/QSRs) photons-IG *B*s NLED, keep in mind! such background $\vec{B}$s are extremely weak!
- A Lagrangian $L = L(F)$ describing photon NLED should depend on $F \equiv F_{\mu\nu}F^{\mu\nu}$ in a nontrivial fashion!
- Interestingly, a study of potential variations of the fine structure constant $(\alpha) \longleftrightarrow$ NLED Lagrangean [12]

[a] M. Marklund, Padma K. Shukla, [Rev. Mod. Phys. 78, 2, 591 (2006)] derived a set of equations describing nonlinear propagation of photons in a radiation plasma. See also Burke et al.[3] who proved that ED in a vacuum pervaded by *B*s is dominated by NL effects

Overview on Nonlinear electrodynamics

What kind of Lagrangian we can look for?

- We use the NLED Lagrangian (introduced in Ref.[6])[a]

$$S = \int \sqrt{-g}\left(-\frac{F}{4} + \frac{\gamma}{F}\right) d^4x \; , \qquad (1)$$

- Its original purpose: to bring in a NLED model for *DE*[b]
- z changes (depending on B) $\longrightarrow$ $\longrightarrow$ changes in *LD* (*B*s NL evolution over cosmic scales!
- Physical motivations: Heisenberg-Euler and Born-Infeld NLED! Valid for extremely high *B*s[16, 17, 15])
- In nature not only such very strong *B*s exist! ... It appears promising to investigate also super weak field frontiers!
- Conceptual advantages of (1): it involves only EM fields! neither scalar fields nor Extra-dims or BWs

[a] Lagrangian is gauge invariant! $\longrightarrow$ charge conservation is guaranteed!

Overview on Nonlinear electrodynamics

What kind of Lagrangian we can look for?

- For high values of F dynamics $\longrightarrow$ Maxwell's ($\longrightarrow$ recovery of Coulomb law!) except small corrections $\longleftrightarrow \gamma$
- At low F strengths, $1/F$ term dominates[7]! (Such term $\longleftrightarrow$ effects on photon-$\vec{B}$ interaction in IG space)
- Consistency with observations: CMB bounds (Ref.[6]) $+$ explanation Pioneer 10/11 anomaly [18] $\longleftrightarrow \downarrow\downarrow \gamma$
- EM field in Eq.(1): Source in EEs! $\longleftrightarrow$ universe toy model displaying acceleration!
- Accel. phase: when NLED term takes over other fields
- $B \neq 0 \longrightarrow$ Cosmic substratum: collection of non-interacting k fluids! EoS: $p_k = \left(\frac{4k}{3} - 1\right) \rho_k$ :::: ordinary radiation: $(p_1 = \frac{1}{3}\, \rho_1) +$ a fluid: $p_2 = -\frac{7}{3}\, \rho_2$
- Component with $p < 0 \longrightarrow\longrightarrow$ accelerate expansion (with $w < -1$, i.e. phantom-like dynamics)

Effects of NLED in Cosmology

Friedmann model with $T_{\mu\nu}$ from NLED

- Introducing the notation[a] EM field is source for FLRW model if:
  $\langle E_i \rangle_{|V} = 0$, $\langle B_i \rangle_{|V} = 0$, $\langle E_i B_j \rangle_{|V} = 0$, $\langle E_i E_j \rangle_{|V} = -\frac{1}{3} E^2 g_{ij}$,
  and $\langle B_i B_j \rangle_{|V} = -\frac{1}{3} B^2 g_{ij}$[b]
- Such conditions fulfilled $++++$ general NLED $L(F) \longrightarrow$ ($L_F = \frac{dL}{dF}$, $L_{FF} = \frac{d^2L}{dF^2}$):[c]

$$\langle T_{\mu\nu} \rangle_{|V} = (\rho + p) v_\mu v_\nu - p\, g_{\mu\nu}, \tag{2}$$

$$\rho = -L - 4E^2 L_F, \qquad p = L + \frac{4}{3}(E^2 - 2B^2) L_F,$$

---

[a] Due to isotropy of spatial sections in FLRW model, an average procedure is needed if EMs are to act as a source of gravity [8]. The volumetric spatial average of X, at the time t, reads: $\langle X \rangle_{|V} \equiv \lim_{V \to V_0} \frac{1}{V} \int X \sqrt{-g}\, d^3x$ $V = \int \sqrt{-g}\, d^3x$, and $V_0 >>>$ time-dependent three-volume. (Here the metric sign convention (+, −, −, −) applies.)

Effects of NLED in Cosmology

Friedmann model with $T_{\mu\nu}$ from NLED

- After Ref.[6], we realized that $L(F)$ in Eq.(1) $\longrightarrow\longrightarrow$ change in putative z! $\longrightarrow\longrightarrow$ change in actual source LD

$$D_L = rS(r)(1+z)\Big|_{r_s}, \tag{3}$$

r: radial coordinate :: $S(r)$: function $r \longleftrightarrow$ geometry (model) :: r_s: actual position

- Accounting NLED effects, distance of far-away sources $\longrightarrow\longrightarrow\neq$ $D_P(r)$

$$D_P = \int_0^{r_s} \sqrt{-g_{11}}\, dt \tag{4}$$

- Highlight: Cosmological B should evolve to create actual D_P vs. observed D_L difference!

Overview on NLED (cont.): Investigating effects on

Evolution of surface of discontinuity of F in vacuum $+\vec{B}$s

- By extremizing the Lagrangian $L(F)$, with $F(A_\mu)$ (potentials A_μ) $\longrightarrow$ [9] (∇_ν: covariant derivative)

$$\nabla_\nu (L_F F^{\mu\nu}) = 0, \tag{5}$$

- Besides, EM field cyclic identity

$$\nabla_\nu F^{*\mu\nu} = 0 \quad \Leftrightarrow \quad F_{\mu\nu|\alpha} + F_{\alpha\mu|\nu} + F_{\nu\alpha|\mu} = 0 \tag{6}$$

- By taking discontinuities of the field Eq.(5) one gets [10]

$$L_F f_\lambda{}^\mu k^\lambda + 2L_{FF} F^{\alpha\beta} f_{\alpha\beta} F^{\mu\lambda} k_\lambda = 0 \ , \tag{7}$$

- Eqs. above + discontinuity of Bianchi identity $\longrightarrow$

$$f_{\alpha\beta} k_\gamma + f_{\gamma\alpha} k_\beta + f_{\beta\gamma} k_\alpha = 0 \tag{8}$$

Photon propagation in NLED:

Photon dynamics

- A scalar relation from contracting eq.(8) with $k^\gamma F^{\alpha\beta} \longrightarrow$

$$(F^{\alpha\beta} f_{\alpha\beta} g^{\mu\nu} + 2F^{\mu\lambda} f_\lambda{}^\nu) k_\mu k_\nu = 0 \tag{9}$$

Straightforwardly we find two distinct solutions: when

1. $F^{\alpha\beta} f_{\alpha\beta} = 0 \Longrightarrow$ mode follows standard null geodesics!
2. $F^{\alpha\beta} f_{\alpha\beta} = \chi \Longrightarrow$ **mode follows effective metric**!

- (1) $+$ absence of charge currents $\Longrightarrow$ [a] only light-ray having a_β and k_α such that $f^{\alpha\beta} k_\alpha a_\beta = 0$ will follow geodesics in $g_{\mu\nu}$! (quite exceptional case!)
- (2) $\Longrightarrow$ **Any other light-ray will propagate on the effective metric** Eq.(10, given next!)

[a] Following Lichnerowicz [11]: $f^{\alpha\beta}$ can be decomposed: propagation vector k_α $+$ spacelike vector a_β ($\perp k_\alpha$) describing wave polarization

Photon propagation in NLED:

Reaching the effective metric for light !

- Eqs.(7)-(9) $\longrightarrow$ field discontinuities propagate on [5]

$$\underbrace{\left(g^{\mu\nu} - 4\frac{L_{FF}}{L_F}F^{\mu\alpha}F_{\alpha}{}^{\nu}\right)}_{\text{effective metric}} k_\mu k_\nu = 0 \qquad (10)$$

- $\longrightarrow$ photons propagate on geodesics $\neq$ background space-time $g^{\mu\nu}$!
- Finally, taking the derivative of Eq.(10) $\longrightarrow$ [15, 16, 17]

$$k^\nu \nabla_\nu k_\alpha = 4\left(\frac{L_{FF}}{L_F}F^{\mu\beta}F_{\beta}{}^{\nu}\, k_\mu k_\nu\right)_{|\alpha} \qquad (11)$$

- $\longrightarrow$ NL $L(F)$ $\longrightarrow$ force accelerating photon along its path !

Field averaging for model building in cosmology

- Effective contravariant metric reads as (see Ref.[5])

$$g^{\mu\nu}_{\rm eff} \equiv L_F g^{\mu\nu} - 4L_{FF}F^{\mu\alpha}F_\alpha{}^\nu \; . \qquad (12)$$

- With $F_{\mu\nu} = \eta_{\mu\nu}{}^{\alpha\beta}V_\alpha B_\beta$ ::: $F_{\alpha\beta}F^{\alpha\beta} = 2B^2$, "averaging" $\longrightarrow$

$$F_{\mu\alpha}F^\alpha{}_\nu = -B_\mu B_\nu - B^2 h_{\mu\nu}\, , \langle F_{\mu\alpha}F^\alpha{}_\nu\rangle = \langle B_\mu B_\nu\rangle = -\frac{1}{3}B^2 h_{\mu\nu} \qquad (13)$$

- After averaging one gets: $g^{\mu\nu}_{\rm eff} = L_F g^{\mu\nu} + \frac{8}{3}L_{FF}B^2h^{\mu\nu}$ $\longrightarrow$ Eq.(12) then reads

$$g^{\rm eff}_{\mu\nu} = \frac{1}{L_F}g_{\mu\nu} - \frac{8}{3}\frac{L_{FF}B^2}{L_F\left(L_F + \frac{8}{3}L_{FF}B^2\right)}h_{\mu\nu} \; . \qquad (14)$$

- Eq.(14) $\longrightarrow$ z is indeed modified by $L(F)$!! $\longrightarrow\longrightarrow$ actual change: observed D_L w.r.t. D_P

NLED generic modification to cosmological redshift

Computing redshift changes in a general framework

- Friedmann metric (NLED line-element) now reads

$$
\begin{aligned}
ds^2 &= \frac{1}{L_F}dt^2 - \left(1 - \frac{8}{3}\frac{L_{FF}B^2}{\left[L_F + \frac{8}{3}B^2 L_{FF}\right]}\right)\frac{a^2(t)}{L_F}\gamma_{ij}dx^i dx^j \\
&= \frac{1}{L_F}dt^2 - \frac{1}{L_F}\left(\frac{3L_F}{3L_F + 8L_{FF}B^2}\right)a^2(t)dl^2 = 0 \quad (15)
\end{aligned}
$$

- Then, *effective* cosmological redshift z turns out to be

$$
(1+z)|_{\mathrm{eff}} \equiv \frac{c\delta t_0}{c\delta t_e} = \frac{a(t_0)}{a(t_e)}\,\Delta = (1+z)\,\Delta \qquad (16)
$$

$\Delta \equiv [(1+\Phi)^{1/2}\,|_{t_e}]/[(1+\Phi)^{1/2}\,|_{t_0}]$

$\Phi \equiv 8/3(L_{FF}/L_F)B^2$

NLED induced change to cosmic redshift

- In cosmology: Eqs.(14, 16) $\longrightarrow \longrightarrow$ actual z becomes[a]

$$(1+z)|_{\rm eff} = \frac{c\delta t_0}{c\delta t_e} = \frac{a(t_0)}{a(t_e)} \frac{\left(\frac{B^4+\frac{5}{3}\nu^2}{B^4-\nu^2}\right)^{1/2}\Big|_{t_e}}{\left(\frac{B^4+\frac{5}{3}\nu^2}{B^4-\nu^2}\right)^{1/2}\Big|_{t_0}}. \qquad (17)$$

- Effective $z_{\rm NLED}$ vs. B in Fig.-1! :: HDs in Fig.-2!
- If such NLED effect is not properly accounted for $\longrightarrow \longrightarrow$, zs from (QSRs or GALs) direct observations may lead to mistaken interpretation on actual LD!
- Such task could be performed by estimating angular-average of quadratic B-field over IG space

[a] In astrophysics: specific change in gravitational (surface) z for pulsars with very strong Bs [15, 16, 17]

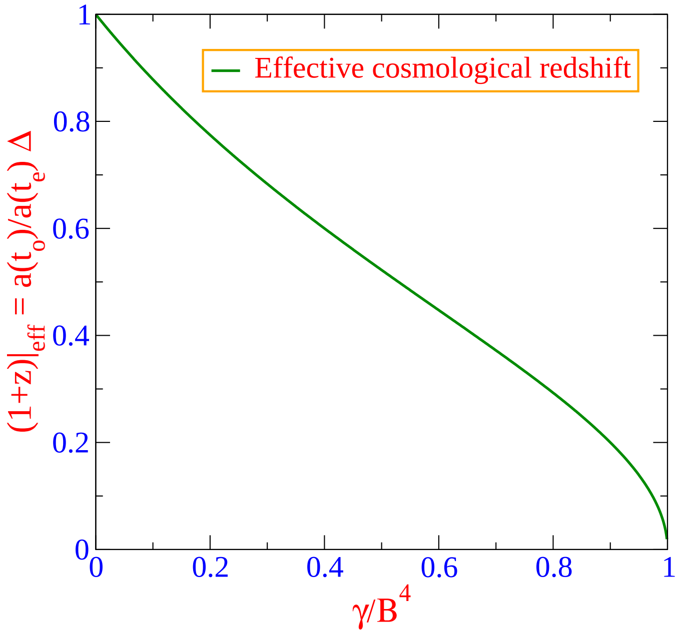
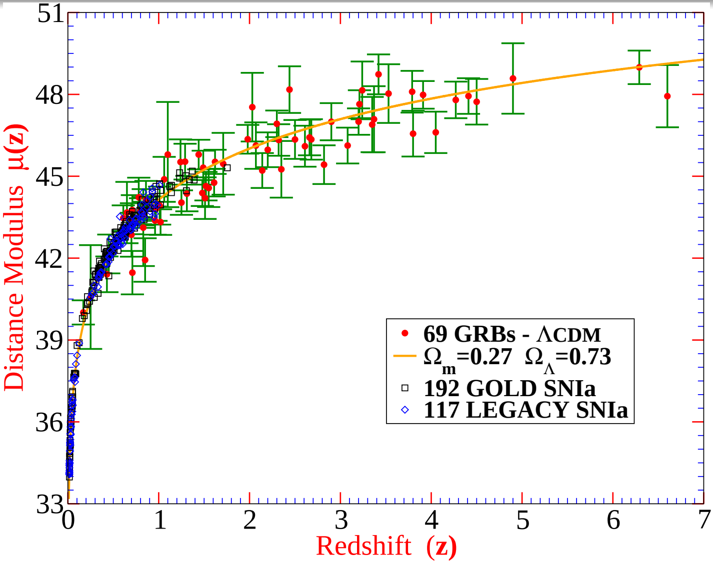
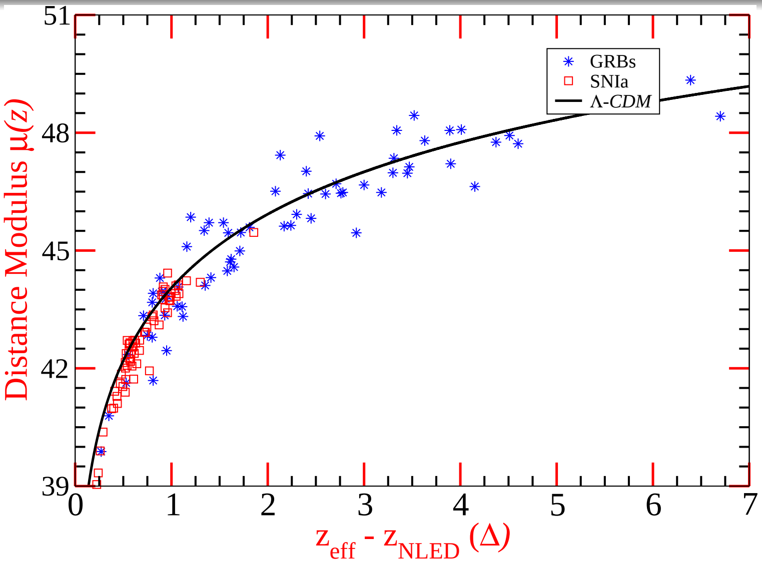

Effective cosmological redshift
$(1+z)|_{eff} = a(t_o)/a(t_e)\ \Delta$
γ/B^4
0
0.2
0.4
0.6
0.8
1

Figure: The effective cosmological redshift $(1+z)|_{\rm eff} = \frac{a(t_2)}{a(t_1)}\Delta$ as a function of the intergalactic B-field strength normalized as γ/B^4, after the NLED correction to the standard cosmological redshift $(1+z) = \frac{a(t_2)}{a(t_1)}$, (here we identify: $t_1 = t_e$, and $t_2 = t_0$). The resulting redshift mimics a cosmological model that has $\Omega_m = 0.27$, as indicated by Eqs.(1,2), when indeed it is built from a Friedmann-Lemaître-Robertson-Walker model which has $\Omega_m = 1$. Notice, however, that the effective redshift does not reach the limit $z = 0$, i.e., the $\gamma/B^4 = 1$ limit is not attainable. In other words $\gamma <<< 0$!!



51
48
45
42
39
36
33
0
1
2
3
4
5
6
7
Distance Modulus μ(z)
Redshift (z)
69 GRBs - ΛCDM
Ω_m=0.27 Ω_Λ=0.73
192 GOLD SNIa
117 LEGACY SNIa


GRBs
SNIa
Λ-CDM
Distance Modulus μ(z)
z_eff - z_NLED (Δ)
51
48
45
42
39
0
1
2
3
4
5
6
7

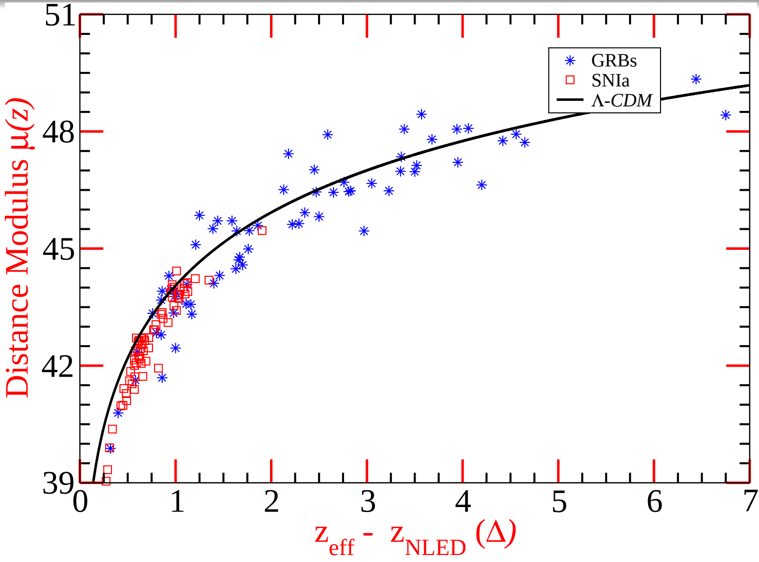


Figure: Hubble diagram of the 69 GRBs sample (filled circles) of Ref.[20] calibrated for Λ-CDM, 192 GOLD SNIa (squares) and 117

LEGACY SNIa (diamonds) samples of Refs.[1, 21], as current observations indicate (No NLED correction included). One may conjecture that most, if not all, of the events presenting a much higher luminosity in this plot could have taken place in sources where the local *B*-field is near the critical one defined from γ. The next two graphs illustrate SNIa, GRBs global shifts of 0.1, 0.15 in *z* (no error bars included). They are intended here solely to illustrate the overall effect. The attentive reader should bear in mind that the NLED correction should indeed be applied to each individual SNIa or GRB event, once knowing (through Zeeman splitting, cosmic rays deflection; i. e., correlation of the direction of such particles with the direction of the emitter, or other astrophysical techniques) the intervening (local) host-galaxy *B*-field. This analysis will be presented elsewhere.

Discussion: NLED induced change to cosmic redshift

NLED redshift correction vs. SNIa challenging observations

- Main result: Eq.(16) !!
- Irrespective of the structure, it is valid for any generic $L(F)$ describing NLED theory, provided field averaging procedure in Eq.(**??**) is held
- Thence, to properly address the actual LD or z of a distant object, NLED effects should first be taken into account!
- Eq.(16) $\longleftrightarrow$ Eq.(17) shows dependence of the NLED effect on the ratio: IG B strength and coupling constant, γ (Fig.-1)
- For values of the ratio $|\gamma|/B^4 \longrightarrow 1$, one obtains redshifts $\downarrow\downarrow$ than the standard FLRW $1+z$! which is recovered in the limit $B^4 >> \gamma$, i.e. $\Delta \longrightarrow 1$!

NLED induced change to cosmic redshift

- Cosmologically crudely speaking, in any NLED theory the PD: $D_P = \int_0^{r_s} \sqrt{-g_{11}}\, dt$, of a source at $r_s \neq$ actual LD: $D_L = rS(r)(1+z)|_{\rm eff}\Big|_{r_s}$!
- Eq.(16) $\longrightarrow\longrightarrow$ NLED correction is already "built-in" in the source actual LD, or z, estimated for instance from the SN host-galaxy absorption lines
- After estimating the IGF B strength[a], the correct z to be plotted in HD ($\mu(z)$ vs. z) is going to be the effective redshift $(1+z)|_{\rm eff}$, after discounting the correction factor Δ provided by NLED (examples in plots c, d in Fig.-2)

[a] Typically: 10^{-11} G (to preserve Λ-CDM predictions for structure formation[25, 24]). For galaxies: 10^{-6}-10^{-8} G)

References I

- S. Perlmutter, et al., Nature **392**, 311 (1998); A. Riess, et al., Astron. J. **116**, 1009 (1998), S. Perlmutter, et al., Astrophys. J. **517**, 565 (1999), J. Tonry, et al., Astrophys. J. **594**, 1 (2003); P. Astier, et al., Astron. & Astrophys. 447, 31 (2006)
- F. Mannucci, M. della Valle, N. Panagia, *H*ow many supernovae are we missing at high redshift?, MNRAS 377, 1229 (2007). e-print astro-ph/0702355
- D. L. Burke et al., Phys. Rev. Lett. 79, 1626 (1997)
- M. T. Murphy et al., MNRAS 327, 1223 (2001)
- M. Novello, et al. Phys. Rev. D 61, 045001 (2000)

References II

- M. Novello, S. E. Pérez Bergliaffa and J. M. Salim, Phys. Rev. D 69, 127301 (2004)
- Notice that on dimensional grounds, $\gamma = \hbar^2 \times \nu^2$, where ν is a fundamental constant with dimension of length^{-4}.
- R. Tolman and P. Ehrenfest, Phys. Rev. **36**, 1791 (1930).
- J. Plebanski, Lectures in nonlinear electrodynamics (Nordita, Copenhagen, 1970)
- J. Hadamard, Leçons sur la propagation des ondes et les equations de l'Hydrodynamique (Hermann, Paris, 1903). Definitions follow Hadamard's[**?**]:
  EM field surface of discontinuity: Σ
  Field continuous when crossing Σ
  $, \longrightarrow$ finite discontinuity

References III

These properties are specified as follows:
$[F_{\mu\nu}]_\Sigma = 0$, $\left[F_{\mu\nu|\lambda}\right]_\Sigma = f_{\mu\nu}k_\lambda$,
$[F_{\mu\nu}]_\Sigma = \lim_{\delta\to 0^+}(J|_{\Sigma+\delta} - J|_{\Sigma-\delta})$: discontinuity of arbitrary function J through Σ
$f_{\mu\nu}$: discontinuity of the field
$k_\lambda = \partial_\lambda\Sigma$: propagation vector
Symbols "$_|$" and "$_{||}$" stand for partial and covariant derivatives

A. Lichnerowicz, *Elements of Tensor Calculus*, (John Wiley and Sons, New York, 1962). See also *Relativistic Hydrodynamics and Magnetohydrodynamics* (W. A. Benjamin, 1967), and *Magnetohydrodynamics: Waves and Shock Waves in Curved Space-Time* (Kluwer, Springer, 1994)

References IV

- J.-P. Mbelek and H. J. Mosquera Cuesta, *Nonlinear electrodynamics and the variation of the fine-structure constant*, **in press by MNRAS**. e-print: arXiv astro-ph/0707.3288
- V. A. de Lorenci, et al., Phys. Lett. B 482, 134 (2000)
- H. J. Mosquera Cuesta, J.-P. Mbelek, *Nonlinear electrodynamics correction to the Compton shift*, in preparation
- H. J. Mosquera Cuesta, José A. de Freitas Pacheco, José M. Salim, Int. J. Mod. Phys. A 21:43-55 (2006)
- H. J. Mosquera Cuesta, José M. Salim, Mon. Not. Roy. Ast. Soc. 354: L55-L59 (2004)

References V

- H. J. Mosquera Cuesta, José M. Salim, Astrophys. J. 608:925-929 (2004)
- J.-P. Mbelek, H. J. Mosquera Cuesta, M. Novello and J. M. Salim, Eur. Phys. Lett. 77, 19001 (2007)
- J. P. Vallée, New Astron. Rev. 48, 763 (2004)
- Schaefer B. E., Astrophys. J. 660, 16 (2007)
- L. Balázs, et al., Astronom. Nachricht. 327, Issue 9, 917 (2006)
- Thomas P. Sotiriou, Stefano Liberati, *Metric-affine f(R) theories of gravity*, Annals Phys. 322:935-966 (2007). e-Print: gr-qc/0604006

References VI

- M. Novello, et al., *Rebouncing in a cycling universe*, arXiv:0802.1875v1 [astro-ph]
- E. Waxman, P. Coppi, Astrophys. J. 464, L75 (1996). See also, E. Waxman, J. Miralda-Escudé, Astrophys. J. 472, L89 (1996)
- J. P. Vallée, Astrophys. J. 360, 1-6 (1990); Astron. and Astrophys. 239, 57-62 (1990); Astronom. J. 99, 459-462 (1990)